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BULK PLANT RISK OPTIMIZATION

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BULK PLANT RISK OPTIMIZATION

by

F.G. Bercha and Associates Limited
Calgary, Alberta

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It has not undergone rigorous technical review by the Environmental Impact Control Directorate and it does not necessarily reflect the views and policies of Environment Canada.

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Research and Development Division
Environmental Emergency Branch
Environmental Impact Control Directorate
Environmental Protection Service
Environment Canada
Ottawa, Ontario
K1A 1C8

December, 1982

FINAL REPORT

On

BULK PLANT RISK OPTIMIZATION

To

DEPARTMENT OF THE ENVIRONMENT
ENVIRONMENTAL PROTECTION SERVICE
HULL, QUEBEC

By

F.G. BERCHA AND ASSOCIATES LIMITED
CALGARY, ALBERTA

DECEMBER, 1982

December 15, 1982

Department of the Environment
Environment Protection Service
15th Floor, Place Vincent Massey
351 - St. Joseph Blvd.
Hull, Quebec
K1A 1C8

Attention: Mr. M. Fingas

Dear Sir:

Re: Bulk Plant Risk Optimization

I am pleased to submit herewith the Final Report for the above work.

Essentially, the work involved development of a risk-cost optimization analysis of hydrocarbon storage plants. The methodology developed and utilized is general and applicable to bulk storage plants of any type, configuration, design, capacity, or location, provided the key quantitative descriptive parameters are available.

As you will note from the Final Report, following the Executive Summary and Introduction, chapters follow giving detailed descriptons of the bulk plant physical systems, the analytical methodology utilized herein, the software package and input variables, representative results, and conclusions and recommendations.

I thank you for the cooperation and advice you have provided throughout the work and look forward to your comments on this Final Report.

Yours truly

F.G. Bercha, P. Eng.
President

FGB/njf

ABSTRACT

The capability to quantify and relate bulk plant capital, operating, and accident costs, and to optimize accident risk within a set of physical, operational, and economic constraints was generated. This generation was achieved through systematic prosecution of the following three main tasks:

(a) Information Gathering.
(b) Risk and Optimization Analysis.
(c) Result Generation.

In the information gathering phase, data were obtained from public and private sources on general crude oil bulk plant operations, plant accident scenarios, accident statistics, plant operating and capital costs, and associated accident costs. A risk optimization analysis of bulk plant operations within the constraints of economics of risk was then developed. The risk analysis portion was carried out utilizing conventional fault tree techniques. Association of the risk and cost through a fault tree modification to generate a cost tree for the optimization of risk within economic constraints utilizing cost and fault tree networks was carried out through the development of a non-trivial software package capable of optimizing over variable inputs for one or more base events. Generation of local and global maxima and minima for total plant operating and capital costs was shown to be achievable utilizing the optimization procedure. Results generated included specific numerical results as well as ones illustrating general trends relative to operational and economic issues associated with bulk plant operations. The software package, in addition, was provided with two optional operating modes; namely, an approximate mode in which only certain key parameters for bulk plants had to be input and a more refined mode involving numerous inputs and more refined outputs. General conclusions, relating to risk causes, risk minimization motivation, operational risk parameter priorization, and a number of specific risk related items were presented. Recommendations for further work directed at the improvement of reliability of bulk plant operations as well as provision of a better understanding of such operations were presented.

ACKNOWLEDGEMENTS

Funding provided for this investigation by Department of the Environment, Environmental Protection Service, is hereby gratefully acknowledged. Appreciation for the cooperation and assistance provided by the scientific authority for the work, Mr. M. Fingas, is also expressed.

It should be noted that the main investigators in the work on behalf of F.G. Bercha and Associates Limited were Dr. F.G. Bercha, Dr. J.G. Rokne, and Mr. R. Kurchaza.

EXECUTIVE SUMMARY

1. Summary

An analysis of bulk plant capital, operating and accident costs within the context of operational conditions was carried out. These costs and their interrelationship were used to optimize bulk plant accident risks within a set of physical, operational and economic constraints. The following main tasks were carried out:

(a) Information Gathering.

(b) Risk and Optimization Analysis.

(c) Result Generation.

In the information gathering phase, information was obtained from public and private sources on general bulk plant operations, bulk plant accident scenarios and associated statistics, bulk plant operating and capital costs, and accident costs. Operational and accident event data were available from records on a local, national, and international level. Cost data relating to accident optimization was, however, particularly difficult to obtain. A heuristic distinction was made between accident and operator costs for the purposes of carrying out the current study. The body of information obtained from empirical and statistical sources served as a reasonable basis for the current work and should provide a good foundation for the execution of more rigorous analyses in the future.

The risk optimization analysis of bulk plant operations was developed within the constraints of economics of risk. The risk analysis portion of the work was carried out utilizing conventional fault trees modified to generate a cost tree. The concept of a cost tree is relatively new in the literature. Algebraic conventions were altered in order to correspond to cost rather than probabilistic computations. The interface between the probabilistic fault tree and the associated economic cost tree through the utilization of cost factors, although relatively simple, has not previously been reported in the literature. Optimization was achieved through a systematic perturbation of accident probabilities with a deterministic functional variation of associated costs. The generation of local and global maxima and minima for total plant operating and capital costs was shown to be achieveable utilizing the optimization procedure. Although the validity for certain of the optimization procedures was intuitively evident, the general validity of the specific numerical economic results generated is contingent on the accuracy of the cost factors. The general principle of risk optimization utilized herein appears to have been adequately implemented through the optimization technique developed.

The results generated included specific numerical results as well as results illustrating general trends relative to operational and economic governing parameters. The numerical results were generated utilizing a software package developed specifically for the current project. This software package may be operated in several modes, including a preliminary result generation mode and a refined analytical mode. The preliminary result generation mode only requires a small number of inputs in order to operate making it virtually universally usable. The more refined mode requires that certain internal parameters described in the report must be modified in order to reflect secondary and higher order effects in the optimization procedure. Specific numerical results generated include the following:

(a) Individual event optimization.
(b) Dual event optimization.
(c) Multiple event optimization.
(d) Plant type variation investigations.

The numerical studies revealed the following general trends:

(a) Human error is the principal cause for spill in bulk plant operations. It is also the most difficult to predict and control because of its sensitivity to operating and environmental parameters.
(b) External hazards such as sabotage, collision, weather, tsunami, and earthquakes, are uncontrollable but are normally quite insignificant.
(c) The catastrophic spill event is of principal concern because of its major contribution to spill volume.
(d) Legislation and levying of penalties adds to spill prevention motivation.
(e) The per barrel cleanup costs are inversely proportional to the magnitude of the spill.

2. Bulk Plant Physical and Operational Parameters

A bulk plant or tank farm, generally serves to provide temporary storage for hydrocarbon liquids at intermediate points between wellhead and consumer distribution. Such storage is required at the wellhead, at loading and unloading terminals at refineries for feedstock and product, and at production distribution centres, and product utilization sites. Crude oil, gasolines, naptha, kerosene, oils, and bitumen are some of the most frequently stored liquids. They exhibit different properties of viscosity, weight, volatility, and flash point, and, accordingly, handling procedures and facilities differ with products handled. Specific bulk plant functions also dictate the nature of the facility. Size, interface type, tank configuration, layout, control systems, and other characteristics are defined by operational requirements.

The main physical component of a bulk plant is the storage tanks. These are differentiated on the basis of roof type into fixed roof, floating roof, internal floating deck and variable vapour space tanks.

Piping, valves, and pumps consititute the balance of the principal physical components. These are operated through automatic control systems designed to failsafe.

Although the nature of the operations at most bulk plants is comparable, the level of the operations can vary significantly depending on the peak throughputs which in turn depend normally on the mode of supply and the customers served. All terminals receive and distribute products by means of one or more of the following transportation systems:

(a) Rail tankers.

(b) Tank trucks.

(c) Tank ships.

(d) Pipelines.

The number of personnel employed in a terminal naturally varies with the magnitude of the operation. As a typical example, a medium sized inland facility with an average annual throughput of ten million barrels employs seven operators and three maintenance personnel, which include those required to staff the transfer docks.

Many tank farms are automated to the extent that one or two men can control all transfer operations from within a centrally located control room. Older facilities, however, still require tank men to regulate and monitor flows into and out of each individual tank. There, good communication is particularly important since it forms the principal element in maintaining a reliable operation.

3. Bulk Plant Accident Events

Accidents that result in the spills of petroleum products at major bulk storage terminals can be attributed to one, all or any combination of design error, operator error, equipment failure and miscellaneous other causes.

The design function includes plant layout, location, tank layout, dikes, foundations, drainage, foam systems, water supplies, barricades, security arrangements, and other considerations. Specific equipment design is considered to constitute a component of equipment reliability.

Operator errors include both operating and maintenance related errors that together constitute the principal source of spill accidents. Operator activities are associated primarily with the movement of product from one terminus to another, whereas maintenance activities are aimed at ascertaining that the hardware functions adequately.

Equipment failure is caused by physical component failures of various types. Common areas of equipment failure are welds, pressure or vacuum relief valves, fittings, worn valves, tank bottoms, flow rate indicators and frangible roof welds.

4. Analysis

Previous work in risk analysis of hyrdocarbon facilities by the authors has included only the determination of risk, or accident probability, and risk expectation, or expected accident volume per unit time. Such analyses, accordingly, have concerned themselves primarily with the prediction of event-space-time configurations, without considering cost and consequence. The methdology utilized in such investigations as well as others is that of fault trees, a well proven direct probabilistic nonlinear network technique historically evolved through the need to analyze failure probabilities of systems without history.

For the current work, fault trees will again be utilized as a basis for evaluating accident risk. However, in order to evaluate spill expectations, cost relationships, and to optimize cost, the basic fault tree concept was extended to develop expectation and cost trees. Optimization was achieved through superimposition of a direct nonlinear optimization search technique on the cost tree.

In the current study the hierarchy of probability events was limited by both the cost analysis and the difficulty in assigning probabilities to the basic events. The uppermost events in the bulk plant probability hierarchy therefore include the seven major accident events that result in petroleum spills in the bulk plant, as follows:

(a) Tank overflow.

(b) Tank leakage.

(c) Tank rupture.

(d) Ancillary equipment leak.

(e) Ancillary equipment spill.

(f) Fire or explosion.

(g) Other.

5. Software Package and Input Variables

The software package developed for this study consists of specific programs written in the Fortran IV language and executed on a CDC 6400 time-sharing general-purpose computer system. The scope of the study necessitated the development of two programs; namely, one to permit sensitivity computations for individual basic events, and one to generate results using optimization techniques for any number of basic events.

The input data to the programs consisted of the probabilities of the basic events, cost for the events as well as pertinent information for a specific bulk plant. This specific information consisted of the following:

(a) Number of operations per year.

(b) Number of tanks filled per operation.

(c) Factors relating to environment, location, amount of vapour, degree of automation.

(d) Yearly throughput.

(e) Volume spilled/accident type.

(f) Associated costs/accident type.

The probabilistic and cost variables were evaluated on the basis of available empirical risk data. These data were collected mainly from applicable statistical sources, previous reports, field investigations, and expert opinions.

6. Results

Two principal categories of results were generated; namely, single and multiple input optimization results.

The single event input optimizations were essentially cost sensitivity studies directed at establishing curves giving the relationship between cost and probability for the accident event under consideration. Multiple input investigations were in essence optimizations of the entire bulk plant for a given set of factors.

All runs were initiated on the basis of perturbations of the base case bulk plant. This base case bulk plant was the model of an average bulk plant which was studied in considerable detail.

The following sensitivity studies, individual event optimizations, were carried out:

(a) Pipe corrosion

(b) Seal leaks

(c) Inadequate inspections

The multiple event optimizations were carried out for two events and for seven events.

Finally, numerical studies were carried out for bulk plants of different types and capacities in order to demonstrate applicability of the methodology to these types of plants.

7. Conclusions

A. Operator Error

Of the seven major accident types examined, operator error during tank charging operations was the main contributing factor. Human error classification for the remaining accident types is principally related to maintenance activities to be discussed later.

From the analysis it was concluded that:

(1) Training may assist in eliminating the errors associated with inexperience.

(2) Human errors are pervasive. Both training and experience fail to completely eradicate accidents due to human failings.

(3) Operator reliability is significantly affected by the working conditions.

(4) The implementation of the high-level alarm is most beneficial if applied only in a passive capacity.

(5) Operator spill incidents are significantly influenced by company policy.

B. Equipment Reliability and Maintenance Errors

The relationship between equipment reliability and maintenance as an operating accident prevention activity is readily discerned from the analysis. It was established that the maintenance function could be separated into three distinct roles, namely repair, service, and inspection, each essential to the operation of any installation.

If the total annual bulk plant expenditure was minimized using the simulation model, then this implied that the following conclusions were reached:

(1) Spill incidence probability is reduced by improved training.

(2) The implementation of intricate or novel equipment may reduce accident costs.

(3) The implementation of automatic safeguarding devices can significantly reduce spills and depress overall operating expenditures.

(4) Human related design and construction unreliabilities must be considered in the appraisal of the reliability of any hardware components.

(5) An inexperienced maintenance man is inclined to make more technical errors; however, an experienced individual is prone to overconfidence which can also result in spill incidents.

(6) Surveillance of contract workers while on site is necessary.

(7) The value of any system is limited by its cheapest components.

(8) Equipment reliability is proportional to frequency of repair.

(9) Scheduling of preventive maintenance work is more cost efficient than clean-up and repair costs associated with failures.

(10) Replacing worn parts rather than repairing them increases equipment reliability and reduces associated long-term costs.

C. Design Error

Failures due to engineering design errors are those that historically have the lowest incidence of occurrence. The preparation and continuous refinements of codes and standards over the years have resulted in guidelines recognized and used throughout the design industry. Hazard analysis is an important aspect of the designer's function, enabling him to identify weaknesses in the system.

D. Scale Effects

In the analysis of facilities with different throughputs, numbers of annual operations and numbers of tanks filled per operation, the following conclusions were reached:

(1) The transfer of petroleum is the primary contributor to spill incidence.

(2) The greater the annual throughput, the lower the per barrel total costs.

(3) Total annual costs increase at a decreasing rate as the size of the plant, measured by the annual throughput, increases.

(4) As the size of the terminal increases, oil spill losses tend to decrease.

8. Recommendations

A. Operational Recommendations

Recommendations directed at optimizing bulk plant operations are as follows:

(1) Formal training programs must be extended beyond the initiation period of an employee's association with the company. Periodic refresher courses reviewing operating procedures and introducing new industrial innovations preserve the employee's prime level of efficiency.

(2) A high level tank alarm installed on each tank will reduce operating costs by reducing costs incurred through overflow incidents. A redundant system consisting of both high level alarms and automatic shutdown devices would not be economically viable, and is therefore not recommended.

(3) Implementation of specialized equipment can be justified if savings in accident cost and productivity exceed the cost of the hardware and increase in costs associated with specialized maintenance.

(4) Errors in plant design are normally the least significant with respect to their contributions to incidents of failures leading to the spill of petroleum. Small improvements in the design stage could, however, potentially alleviate costly human errors during operation.

B. Study Recommendations

Recommendations for further investigative, analytical, and data collection work related to the improvement of risk optimization studies of the type carried out and described herein are as follows:

(1) The development of a comprehensive national system of spill documentation identifying volumes spilled, material spilled, source, cause, extent of damage, percent recovered, contingency procedures effected, and itemizing all costs associated with clean-up including third party and penalty costs.

(2) The refinement of fault tree methodology to better handle industrial problems that require an understanding of the relationship between the probabilities of failure, and the associated costs of prevention, directed towards maximizing economic efficiency.

(3) The comprehensive, in-depth investigations of a number of existing operations to establish an effective data base applicable to the problem under study. Published information is less accurate since interpretation and inferences have been made.

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Approximately 600 million barrels of hydrocarbon liquids are handled by bulk storage plants in Canada each year. It is estimated that of the above values, approximately 0.02% or 120,000 barrels are spilled and not recovered [59, 61]*.

Numerous regulations, guidelines, manuals, and formal programs directed at minimizing spillage at bulk plant operations have been proposed and implemented. Operators have accepted regulatory measures with varying degrees of enthusiasm, often depending on their understanding of the effect of such measures on plant costs. Some work appears to have been done on bulk plant safety [37, 149], and the related problems of accident risk [41, 45, 83, 103]. But the real issue, the connection between accidents and plant costs, does not appear to have been addressed rigorously.

A capability to quantify the relationship between plant cost and accident cost, including realistic consideration of capital and operating costs and the effect of accident prevention programs on them, would indeed provide a powerful criterion for establishing viable bulk plant accident prevention guidelines. A further capability to optimize the level of accident prevention expenditures, within the functional and economic constraints of bulk plant operations, would permit operators and authorities to objectively set relevant criteria.

---

* Numbers in square brackets correspond to publications listed under References.

It is the objective of the current work to generate such an optimization procedure, utilizing methods of probabilistic risk analysis and operations research.

1.2 Scope of Work

Generally, the scope of the work may be subdivided into three main phases as follows:

(a) Information Gathering

(b) Risk and Optimization Analysis

(c) Result Generation, Interpretation, and Reporting

The information gathering phase consisted of a search through the literature on bulk plant operations, spill accident scenarios and rates as well as analytical methodology. Additional information was gathered through plant visits, discussions with operators and constructors, literature, and Government sources.

The analysis phase was carried out in-house, partially utilizing existing methodology [12, 13, 14], and culminating in the generation of the nontrivial risk optimization software system. The analysis generally involved the execution of a spill risk analysis, conversion of spill risk to expectation, transformation of risk expectation into risk cost, and superposition of an optimization procedure on a risk-cost network with a capability to estimate total plant cost variations for different risk levels and associated expenditures. Since such work has not been carried out previously, it was necessary to develop and implement a fault-cost tree optimization procedure, utilizing a meld of operations research and reliability engineering techniques.

The result generation phase involved the quantification of inputs, utilization of the software package developed, and interpretation and presentation of the outputs. The results were generated principally by means of the software package utilizing a CDC 6400 computer, for a range of plant types and constraints. Tabular and graphical forms of the numerical results together with associated interpretation were generated.

In the present report, following this introductory chapter, a comprehensive description of bulk plant operations is presented in Chapter 2, Chapter 3 presents the analytical methodology, Chapter 4 discusses the quantification of input parameters, Chapter 5 gives numerical results, and Chapter 6 gives conclusions and recommendations for further work.

CHAPTER 2

BULK PLANT DESCRIPTION

2.1 General Description

A bulk plant or tank farm, as shown in Figure 2.1, generally serves to provide temporary storage for hyrocarbon liquids at strategic points in their progress from wellhead production to ultimate consumption. Storage is required at the wellhead, at loading and unloading terminals both inland and marine, for refinery feedstock, refinery outputs, production distribution centers, and product utilization sites. Crude oil, gasolines, naptha, kerosene, oils, and bitumen [70] are some of the most frequently stored liquids. They exhibit different properties of viscosity, weight, volatility, and flash point, and accordingly, handling procedures and facilities differ with products handled. Specific bulk plant functions also dictate the nature of the facility. Size, interface type, tank configuration, layout, control systems, and other characteristics are defined by operational requirements. Supertanker terminals must necessarily be able to process large volumes quickly and must possess marine interface facilities. Pipeline fed refinery feedstock plants must allow for fluctuation in feedstock demand and pipeline throughput. Truck or train fed facilities require appropriate unloading racks and should be designed for intermittent feeding.

Generally, functions of bulk plants may be summarized as follows [100, 104, 134]:

FIGURE 2.1 TYPICAL BULK PLANT

(a) To provide a necessary buffer between irregular movement of crude from the wellhead and the steady requirements of the refinery.

(b) To provide a battery in the event of unforeseen interruptions due to temporary economic or functional circumstances.

(c) To provide a battery that can absorb fluctuations in demand.

(d) To provide storage of essential petroleum reserves for emergencies.

For the purposes of the present work, a bulk plant system is defined as that physical and operating system located between the delivery and the exchange flange of the storage facility. It includes tanks, piping, pumps, internal transfer systems, and their operators and operations. It excludes the transportation system to and from the plant, and its interface at receiving and delivery points. For completeness, however, in this chapter, the major methods of delivery and transferring bulk product are discussed.

Crude storage plants are dealt with primarily herein. The methodology developed is, however, general enough to be applicable to other types of product facilities with only minor modifications.

The physical system of the bulk plant can generally be subdivided into the following two main subsystems [104, 134]:

(a) Tankage.

(b) Ancillary equipment, including piping, pumps, valves, power, control, and other equipment.

Operations are clearly variable in nature with changes in function, location, product, scale, and so on, but do have certain general patterns in common. For the purposes of the present work, operations will be subdivided into general operations applicable to bulk plants and spill-related operational aspects. In the balance of this chapter, the two main subsystems of bulk plants will be described and illustrated, general operations of bulk plants will be discussed, and specific accident scenarios will be presented.

2.2 Tanks

2.2.1 General Comments on Tanks

Costs of tankage invariable constitute the principal item incurred as capital expenditure and with the associated pipework constitute approximately 75 percent of the overall capital cost [104].

Storage tanks and vessels are fabricated using a variety of different materials, ranging from stainless steel to plastic, and take numerous geometric forms and sizes, dependent primarily upon their intended usage. These forms include cylinders, ellipsoids, spheres, and tauri. Domestic storage tanks can be capacities of several barrels while tanks serving refineries and major installations may have capacities exceeding a million barrels.

Tanks can be either vertically or horizontally oriented, above or below ground, pressurized or operated at atmospheric pressure. The manner of fabrication is also important, including riveted, sectional, and welded construction, with the latter adopted as the usual form of the major storage terminal installations. The large size of many tanks makes site erection the only feasible method for assembly. Because of the widespread use of welded steel tanks, the current work will concentrate primarily on such tank construction.

2.2.2 Types of Tanks

Differentiation will be made among tank types by roof type. In fact, roof type is the only salient feature that varies significantly among different tank types. This general constancy of features allows a certain amount of flexibility in establishing the most suitable kind of storage, contingent upon the nature of the product stored and desired performance. Fixed roof, floating roof, internal floating deck and variable vapor space tanks comprise the four major classes of tankage.

(a) Tanks with Fixed Roofs.

Storage tanks with fixed roofs have long been used by the petroleum industry, with many thousands having been designed, manufactured, and put into service over the years. They are designed as either pressure or non-pressure vessels, differentiated by the venting system used. The former utilizes a breather vent to minimize vapor losses from stored volatile liquids that would normally occur if the tank was vented atmospherically. In addition it provides protection to the tank from immoderate conditions of pressure or vacuum. The latter, non-pressure vessels, are vented through properly sized free-flow apertures strategically located around the tank perimeters near roof level, allowing unimpeded flow of air and vapours. Such a vent is shown in Figure 2.2.

The fixed roof is normally dome or cone shaped and is supported either on interior columns or entirely by the tank walls.

The fixed roof tank is principally suited to the storage of low-volatile liquids. It derives its advantage over the two other types of tanks considered by minimizing capital expenditure. However, the most noticeable disadvantages of the fixed roof tank include: its constant space characteristic that causes higher breathing, filling, standing, emptying and boiling losses than are incurred by the other tank designs, and a marked increase in the potential for fire or explosion.

(b) Floating Roof Tanks

The development of the floating roof has been an important contribution to petroleum storage operations by significantly minimizing costly vapour emissions. It is comparatively safer from fire or explosion than the fixed roof tank.

The underlying principle of the roof's utility is its capability to move up and down with the changing levels of stored product simply by floating on the surface of the

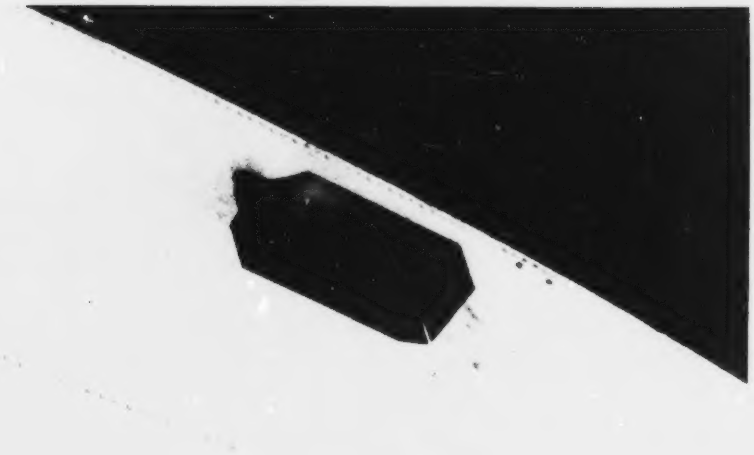


FIGURE 2.2 BREATHER VENT

liquid, thereby reducing the free liquid surface and the volume above the surface where vapour would normally have a propensity for emission. Due to structural considerations, the floating roof has allowed tank capacities to increase tremendously over the fixed roof tank. The pressured fixed roof was economically limited because of its self-supported construction to a maximum diameter of 128 ft. [70], while floating roofs have no theoretical limit.

Two basic types of floating roof have evolved since the principle was first developed; namely, the open pan and the internal floating deck. The latter was first introduced in the early 1920's and installed in fixed roof tanks to allow these tanks to benefit from the advantages that the floating pan offers.

The three most common current varieties of floating roof include the pan (low deck), pontoon (high deck), and the double deck roof.

(i) Pan Floating Roof Tanks

The pan or low-deck roof was the earliest form of floating roof, consisting essentially of a single metal deck resting in contact with surface of the stored liquid. The pan was slightly coned concave downwards, towards the centre, to provide for drainage. The roof had a number of problems affecting its viability. Heavy unevenly distributed snow loads caused it to tip and sink, as did leaks that occurred in the pan. Also, it became apparent that solar energy would heat the pan, boiling the liquid in contact below.

(ii) Pontoon Floating Roof

The pontoon floating roof consists of a torus, fixed to the periphery of the pan along its upper surface, to assist in providing both stability and buoyance to the roof in the event of leakage or heavy superimposed loads. The pontoons overlay about 50% of the deck and as a result provide adequate insulation for the stored product. The central unprotected area can still result in boiling of the product, and cause the pan to bulge slighly upward. The vapour is, however, bound beneath the liquid seal under the pontoon until lower temperatures cause it to recondense and the pan assumes its normal configuration. The pontoon roof is universally employed in the industry and meets accepted standards.

(iii) Double Deck Floating Roof

Double deck floating roofs consist essentially of two complete decks separated by trusses and divided by bulkheads, making the system virtually unsinkable and providing an adequate insulating void to prevent the stored liquid from boiling. The principal disadvantage of the double deck is its high cost.

(c) Fixed Roof Tanks with Internal Floating Deck

The introduction of the internal floating deck has been an important contribution to the commercial petroleum storage industry because it allows existing fixed roof tanks which were once the standard of the industry to economically benefit from the features of the floating roof. The fixed roof provides ample protection from the elements, and consequently the floating deck need act only as a membrane on the liquid surface to control vapour emissions, and not as an external structural element.

The decks are normally constructed from aluminum alloy sheets, polyvinyl chloride, rigid foam (polyisocyanate), glass fibre, and nylon fabric. The closed cell structure of the rigid foam allows decks fabricated from this material to be self-floating, not requiring support from pontoons necessary for the remaining types. Blow-off vent valves and other patented devices have eliminated earlier ballooning and fold-over occurrences prevalent in PVC blankets.

The decks have the advantage of being light and as a result quickly and easily installed. Antirotatation cables are the only mechanism required to maintain stability, and flexible antistatic cables connect the deck to the tank to equalize differences in potential between the two.

This type of storage tank arrangement is superior to the open-type floating roof tanks in terms of performance, because, in addition to vapour emission control, the product is not exposed to contamination, internal corrosion is checked, and the air space between the roof and blanket acts as an excellent insulator permitting the storage of very volatile liquids. Furthermore, the internal deck is adaptable to either a supported or self-supported roof tank.

There are, however, some disadvantages associated with this type of tank. Repairs to the blanket become more difficult and problems may develop in the seals between the deck and any roof support columns. Figure 2.3 shows some fixed column seals to be used in an internal floating deck. For the latter reason it is desirable to keep the number of roof support columns to a minimum.

(d) Variable Vapour Space Tanks

The function of the variable vapour space tank is to reduce atmospheric emissions from the tank, by providing a gas collecting device to act as a buffer. As the vapours expand the collector retains as much vapour as its capacity allows before venting to the atmosphere. Upon cooling, vapour stored in the device condenses back into the tank. These devices derive their greatest utility with tanks subjected to low throughputs [1].

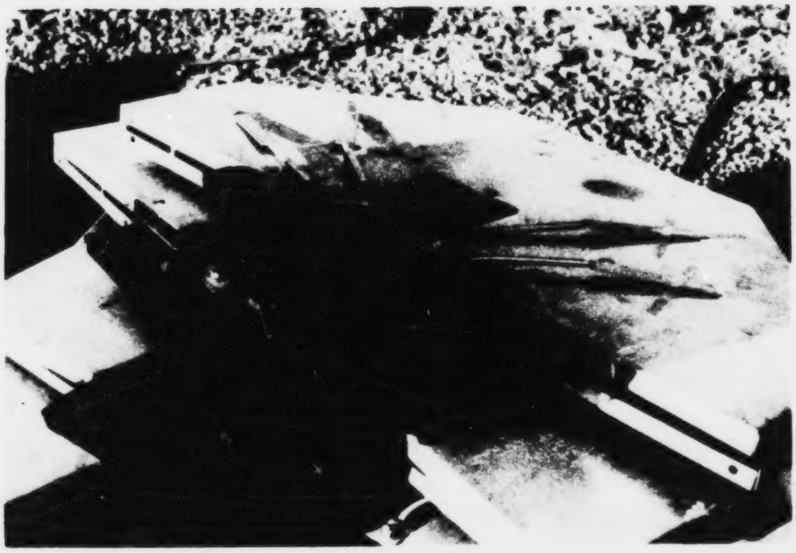


FIGURE 2.3 FIXED COLUMN SEALS FOR INTERNAL FLOATING PAN

2.2.3 Seals

For any variety of floating roof, the fit of the seal around the periphery of the deck between the deck and shell of the tank, is a critical component in utility. It must minimize evaporation of the stored product through the seal, and concurrently allow the deck to operate smoothly. Figure 2.4 shows a typical seal material. The seal must also compensate for any irregularities that might occur if the tank is not perfectly cylindrical.

The seals are normally classified as either metallic or non-metallic. The latter usually imply a variety of continuous fabric seals available in a number of configurations. For a detailed examination of the different types of seals and their applications the reader is referred to [3, 70]. The chief disadvantage of the fabric seal is its susceptibility to puncture during handling, installation or operation that may go unnoticed and defeat the deck's utility. A number of resilient seals are available that reduce the occurrence of such defects [3].

2.2.4 Foundations

The choice of foundation for storage tanks is predicated on tank size and soil conditions.

Where soil conditions are poor but land is readily available, low tanks of large diameter can be erected without the construction of cost pile foundations. If land is limited, however, then a greater storage potential can be achieved by building higher tanks with small diameters, thereby necessitating the construction of more elaborate

FIGURE 2.4 PERIPHERAL SEAL FOR FLOATING PAN

foundations. In areas with ideal subsurface conditions, the erection of tanks with smaller diameters and higher walls would be the most economical solution, increasing storage potential within the boundaries of the plant.

Increases in tank capacities have placed a greater emphasis on foundation design with the realization that uncontrolled settlements could result in weld failures that may lead to catastrophic spills. Particular attention must be directed to subsurface soil condition testing and analysis; and these results together with other economic consideration must form the basis for the type of foundation selected. The variety of foundation designs available includes bituminous macadam sealer applied over a sand cushion, concrete mats, timber mats, a concrete peripheral ring, and, finally, piling--the most costly of the methods [35].

2.3 Ancillary Equipment

2.3.1 Pipework

Pipework, although not as cost intensive as tankage, is an equally essential component in bulk plant operation. Pipework provides a system for the movement of product between storage vessels, and to and from points of distribution, generally illustrated by Figure 2.5 [3, 35, 70, 134].

Pipes are normally laid on supports above ground. Such pipe installation, in addition to economic benefits, allows for inspection and repair access and limits potential for corrosion. The lines are

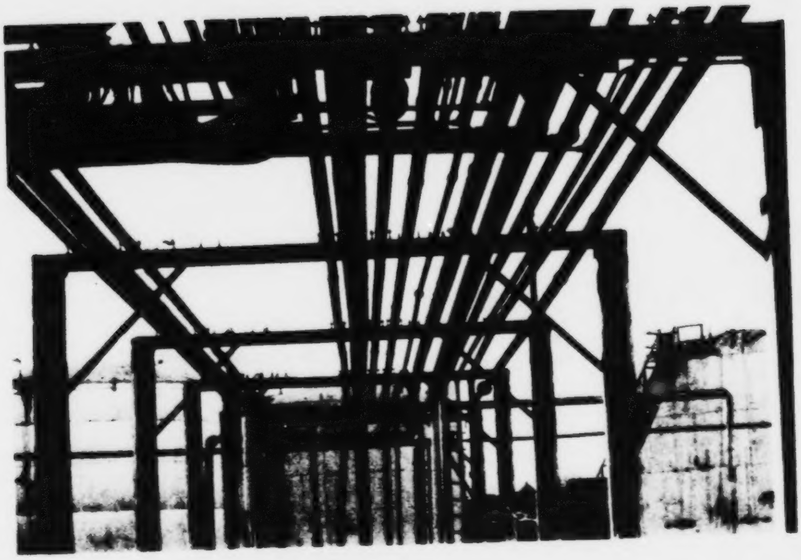


FIGURE 2.5 PIPEWORK

equipped with relief valves to provide for overpressure and drain valves for draining the lines for servicing.

Pipe material is dependent on the type of product handled, although welded steel pipe is the most commonly used. The strings of pipe are generally either welded or flanged together. Valves are installed in the line at strategic locations to control flow rates and direction and to block out lines under repair. The pipe walls normally are painted externally with a corrosion retardent paint before erection, and a normal paint afterwards. Some lines may be insulated contingent upon location, climate, and product moved.

Joints of pipe are normally subjected to rigorous testing both in the fabrication shop and after installation in the field before being placed in service to ensure that required specifications are met. Such tests include:

(a) Tensile and bend tests.

(b) Ultrasonic testing.

(c) Hydrostatic testing.

After installation, piping is pressurized from 85 - 100% of its specified minimum yield strnegth (or at 15% greater than the peak operating pressure) and the pressure is maintained for a length of time suitable for satisfying desired confidence levels. Periodic depressurization-repressurization operations during testing would also induce stresses that would provide reasonable design checks.

Welding the lengths of pipe together is an exacting operation that incorrectly or carelessly executed could lead to a failure culminating in a spill. Rigorous supervision and inspection is necessary and practical to ensure that the job meets specifications.

Buried lines are more susceptible to corrosion than those constructed above grade, and therefore are usually primed and coated with a suitable quality material. Cathodic corrosion protection, often used together with the application of coatings on trunk lines, is sometimes deployed on the small distribution and gathering lines characteristic of terminals.

Above grade lines are also susceptible to the effects of corrosion, although to a much lesser degree than buried lines and consequently simply priming and painting them seems satisfactory.

The expansion and contraction of above grade piping is usually sufficiently provided for by the incidental bends that occur during erection. In the other cases, at one or two points along the length of the line, the line is formed into a horizontal "U" to give it more controlled flexibility. There must also be a certain amount of flexibility designed into the line-tank connection to provide for any differential settlements that occur and could induce unnecessary stresses in the system.

2.3.2 Pumps

Pumps provide a fundamental element in the movement of petroleum through the pipework system from one point to another, and considerable attention must be devoted to the selection and sizing of each unit to ensure efficient operation [3, 8]. The function of pumping equipment is threefold:

(a) To move liquids against the force of gravity.

(b) To increase the rate of flow.

(c) To impel liquids to areas where the liquids are subjected to higher relative pressures.

Pumps are normally subclassified into two broad categories as follows:

(a) Positive displacement pumps.

(b) Kinetic pumps.

The type of pump normally used within a terminal facility is the centrifugal non-self-priming kinetic pump, and although reciprocating and rotary positive displacement pumps have had some application in these installations, the following descriptive summary will deal with the former type exclusively.

Centrifugal pumps can be obtained in one of two configurations, as follows:

(a) Vertical in-line pumps mounted directly onto the line. The impeller is oriented horizontally immediately above the line with any additional impellers mounted vertically above the first (multi-staged). The base motor forms the head of the unit.

(b) Base mounted centrifugal pumps with the motor and impeller within the same horizontal plane either close coupled or visibly two well defined units connected by a drive shaft (Figures 2.6 and 2.7).

The operating principle of the pump involves liquid entering the device to be seized by the impeller, rotating at a very high rate of velocity, and subsequently, the liquid to be whipped centrifugally about the volute and discharged at pressure through the outlet.

Characteristics of centrifugal pumps include:

(a) No reciprocating parts.

(b) Compact unit utilizing space efficiently.

(c) Discharge smooth and continuous.

(d) Cost efficient.

(e) Easily maintained and serviced.

(f) Capable of developing high velocities.

Older models of centrifugal pumps used flexible packing around the pump shaft to minimize leakage and reduce wear, nevertheless these leakages still occurred through the packings if they were too loose. The introduction of the mechanical seal to replace the flexible packing was a major improvement in that it virtually eliminated leakage and lessened maintenance requirements.

The motor that drives the pump is normally electrically powered. Motors are normally rated at 10% over pump requirements.

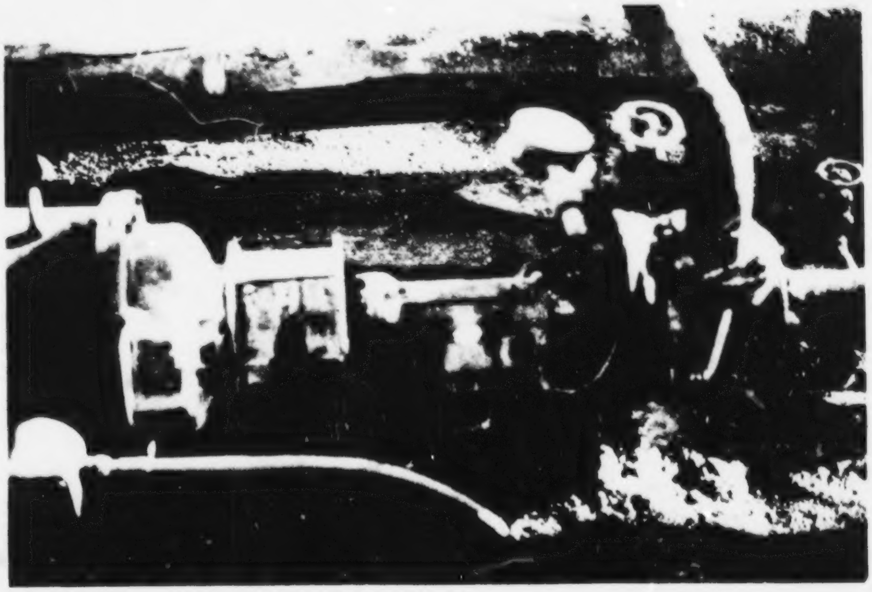


FIGURE 2.6 CENTRIFUGAL PUMP

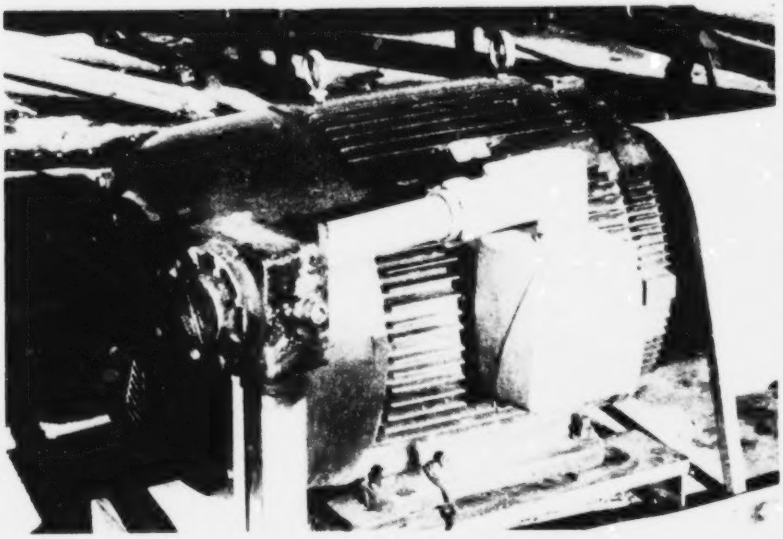


FIGURE 2.7 ELECTRIC MOTOR

For operating in hazardous areas, the units are provided with explosion proof cases.

2.3.3 Valves

Valves are integral components in the operation of a pipework system, providing flow control. Functions of valving include:

(a) Enabling operators to regulate flow rates and movements to, from, and within the plant.

(b) Providing safety relief from the occurrence of such events as reverse flow, surge pressure, and fluid expansion.

(c) Permitting maintenance or service on a length of pipe or vessel by isolating the section from the system.

Some of the valves conventionally used in pipework systems are as follows:

(a) Pressure relief valves, commonly known as "pop" valves; pressure relief valves are designed to automatically open should thermal expansion of the liquid within a section of line exceed predetermined pressure relieving levels, imparting the resulting flow of liquid around a major block valve through a small bypass pipe.

(b) Block valves, located at strategic points along the length of a line allowing certain sections of the line to be blanked off in the event of failure, service or routine maintenance.

(c) Check valves ensuring that liquid flows in one direction only.

(d) Ball valves used for manual throttling of the flow to regulate pressure.

(e) Control valves providing for automatic control of line flow using a built-in governor mechanism or remote control features.

Valves, because of their mechanical nature, will leak if the glands or packing becomes loose, and therefore it is imperative that a good regulatory maintenance program is enforced to limit such effects [3].

2.3.4 Other Equipment

Flanges, manifolds, couplings, flow meters, and fittings are all integral in the transfer-storage operation and must be properly maintained to ensure that leakage or spill is minimized. Examples of such additional equipment items are shown in Figures 2.8 and 2.9.

2.4 Operations

2.4.1 General

Although the nature of the operations at most bulk plants is comparable, the levels of the operations can vary significantly depending on the peak throughputs which in turn depend normally on the mode of supply and the consumers served [8, 100, 134].

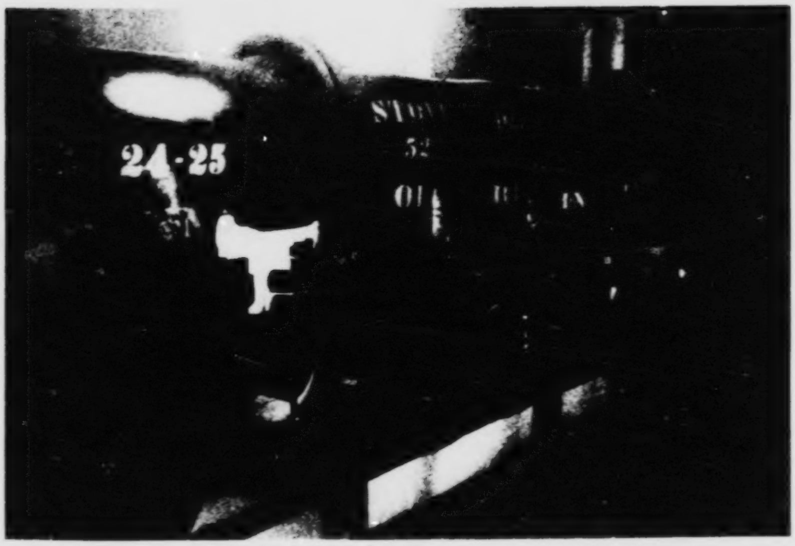


FIGURE 2.8 PIPE MANIFOLD

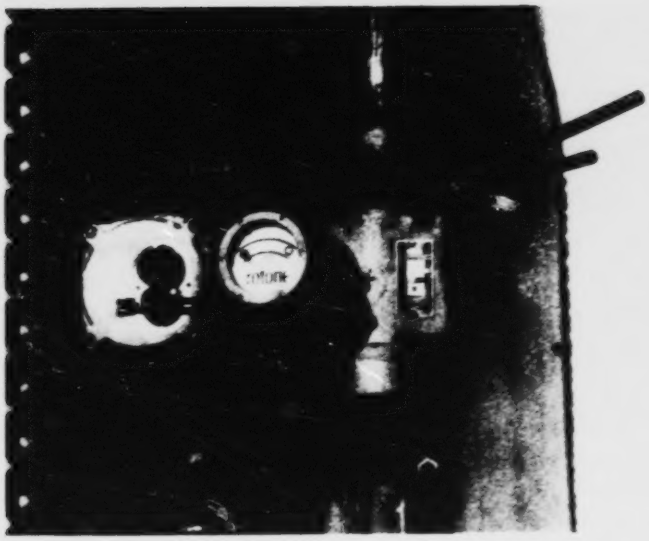


FIGURE 2.9 FLOW METER

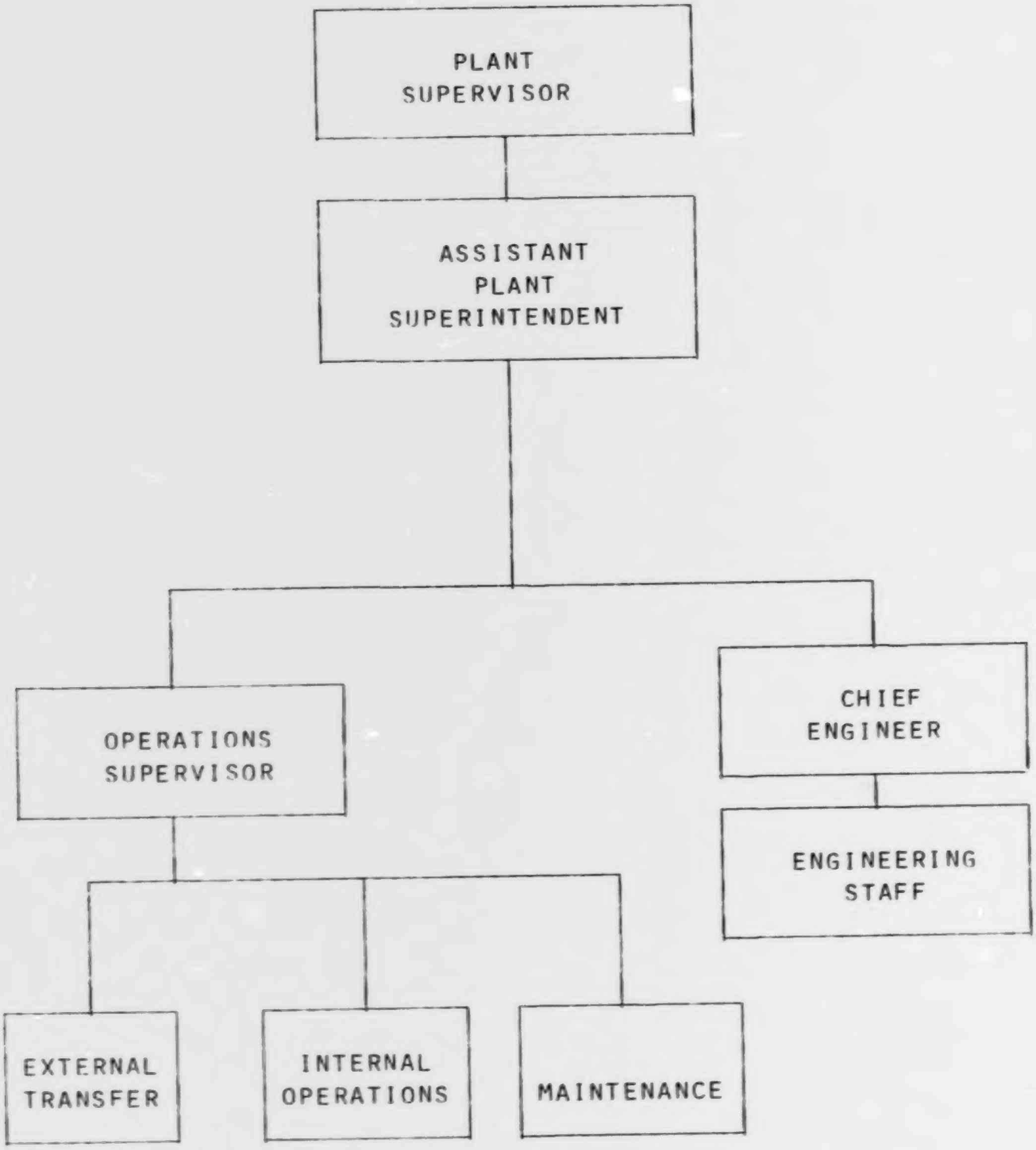


FIGURE 2.10 PERSONNEL HIERARCHY IN BULK PLANT

All terminals receive and distribute products by means of any one or a combination of the following transportation modes:

(a) Pipeline.

(b) Water.

(c) Rail.

(d) Road.

The scope of the present work covers the bulk plant from loading to unloading flange, and thus will not explicitly include the transfer mode. For conceptual completeness, however, in the scenarios described, mention is also made of the transport mode, and Section 2.5 is added to describe in some detail features of the salient alternative transfer modes.

In what follows in this section, a brief description of the significant operations, excluding transfer modes, is given. The description is general, and intended primarily to provide a perspective matrix for the accident scenarios to be discussed in Section 2.6.

2.4.2 Personnel

The number of personnel employed in a terminal naturally varies with the magnitude of the operation. As a typical example, a medium sized inland facility with an average annual throughput of ten million barrels employs seven operators and three maintenance personnel, which include those required to staff the transfer docks. A typical organization chart for a bulk plant is shown in Figure 2.10 while the associated staffing and general employment level indication is shown in Table 2.1.

TABLE 2.1

STAFF DESCRIPTION IN BULK PLANT

No.	Position	Experience (Years)	Status
1	Superintendent	12	Professional
1	Assistant Superintendent	7	"
1	Chief Engineer	5	"
1	Operations Supervisor	7	Operator
1	Terminal Man	8	"
5	Operators	5	"
3	Maintenance Personnel	5	"

2.4.3 Receiving Dock

Liability for product loss at transfer operations rests with the bulk plant. Receiving facilities are generally equipped with redundant metering facilities, to ensure accurate and reliable product reception inventory. Metering facilities are periodically calibrated and frequently tested [100]. Product quality control programs, including sampling and chemical analysis and internal monitoring, are incorporated into the transfer operations. Monitoring of discharges is less stringent since liability is shifted to the carrier or consumer once the product leaves the bulk plant.

2.4.4 Internal Operations

Operators are responsible for the safe and efficient movement of product in the bulk storage plant.

Many tank farms are automated to the extent that one or two men can control all transfer operations from within a centrally located control room such as that shown in Figure 2.11. Older facilities, however, still require tank men to regulate and monitor flows into and out of each individual tank. There, good communication is particularly important since it forms the principal element in maintaining a reliable operation.

Tank overflow is one of the principal causes of product loss. Normally, the tank operators manually stop the flow once desired tank levels are reached. Many tanks are now equipped with high level audible alarms that patch into a control centre should the product level pass an established point. Such alarms are shown in Figures 2.12

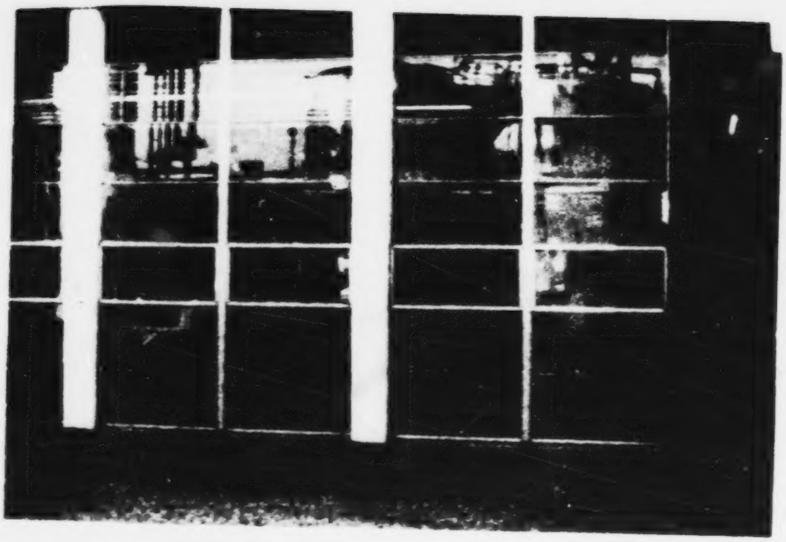


FIGURE 2.11 CONTROL HOUSE

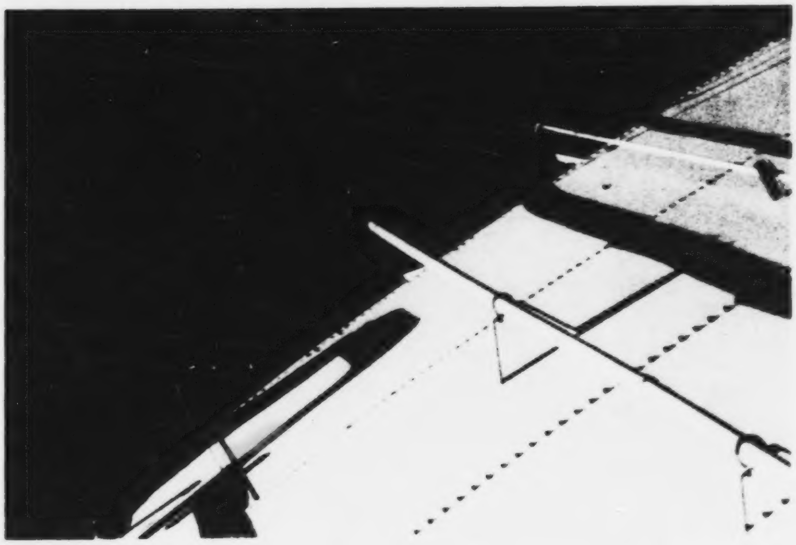


FIGURE 2.12 HIGH LEVEL ALARM

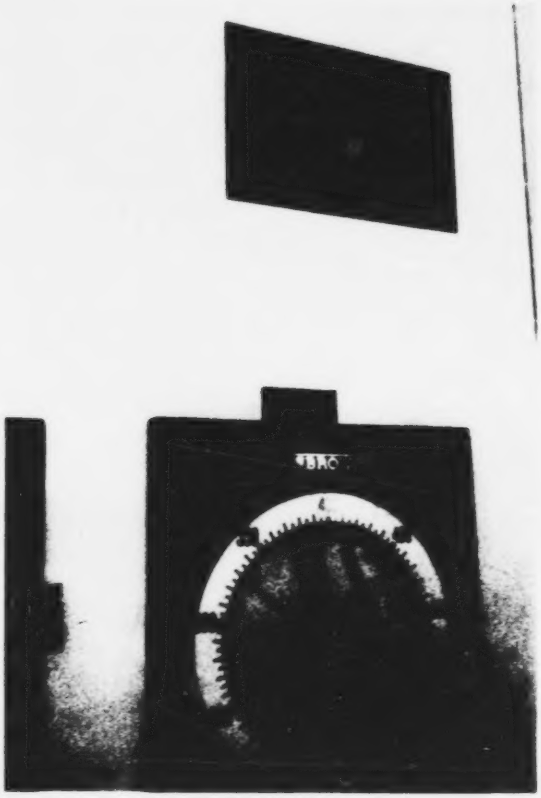


FIGURE 2.13 HIGH LEVEL ALARM
INDICATOR LOCATED IN
THE CONTROL HOUSE

and 2.13. When the alarm sounds, the "freeboard" of the vessel allows time for the operator to shut down the flow. It is imperative that the operator remain on hand during the entire charging process to ensure against overfill. Automatic shutdowns are unusual.

2.5 Transfer System

Product is supplied by means of any one of the transportation modes mentioned above, namely, pipeline, road, rail, and water. A general discussion of each transfer mode is given in what follows.

2.5.1 Pipeline

Trunk lines are used to transport crude or refined products to one or more terminals along their routes. A terminal will often handle more than one product, and as a result, certain products are relegated to specific storage tanks within the installation. The black and white oils are usually separated into different multiproduct lines. Within a line each homogeneous product unit, or "batch", is interfaced against the succeeding unit. A schedule is usually prepared well in advance of the transfer, sequentially identifying the batches to be delivered through the line, detailing volumes of each conveyed. Scheduling allows terminal operators to make necessary preparations for the arrival of the batch interfaces, which are normally transferred into an interface tank before the following batch is routed to its respective storage vessel. The importance of good communication must be emphasized in transfers of this nature, since unexpected interfaces or products out of sequence could result in costly product contamination by being discharged into the wrong tank.

2.5.2 Road and Rail

Rail tankers, and particularly tank trucks, are more commonly used for the distribution of product from the terminal to other small centres. Road vehicles, for example, are normally used to transport gasoline from terminals to supply service stations. Occasionally, though, tank trucks are used to transport product into a terminal, particularly if the terminal is used to provide storage for some product or products employed in an associated refinery. For example, crude oil is delivered to a terminal by tank trucks for use in a neighbouring asphalt plant as illustrated in Figures 2.14 and 2.15.

In the offloading of product from tank trucks the vehicles must be grounded before any transfer begins. Rail-tank cars do not require any special grounding. Both types of vehicles are offloaded through a bottom connection and the product is pumped into a designated storage vessel. This procedure is illustrated in Figures 2.16 and 2.17.

In the loading operation the vehicles are filled by either one of two filling methods as follows:

(a) Top filling

Top filling is the conventional method of loading tank trucks or rail tank cars, and easily recognized by the elaborate loading gantries required (Figure 2.18). Again, in the case of road vehicles, the truck must be suitably grounded and both tank truck and rail car must have the

FIGURE 2.14 TANK TRUCK UNLOADING CRUDE

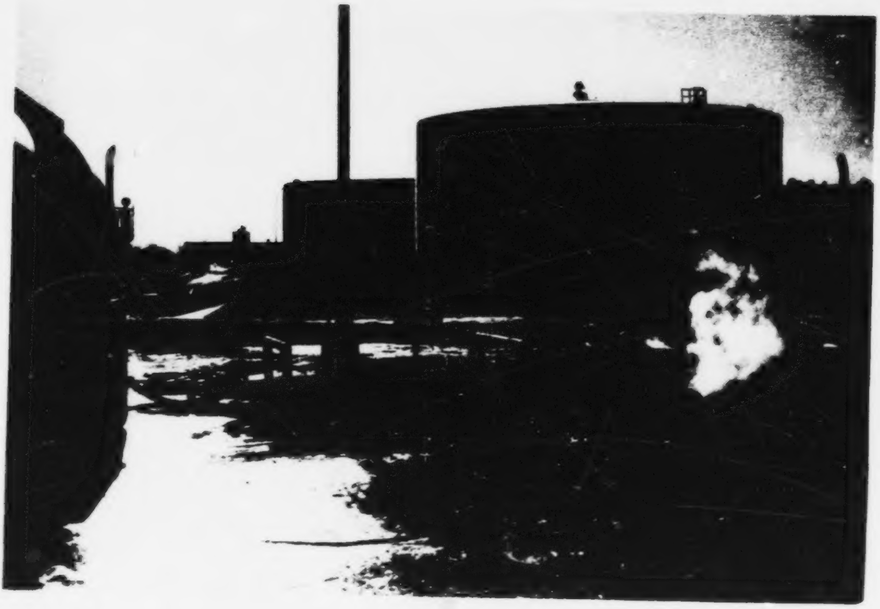


FIGURE 2.15 DETAIL OF TRUCK UNLOADING

FIGURE 2.16 TANK CAR UNLOADING CRUDE

FIGURE 2.17 RAIL UNLOADING TRACKS

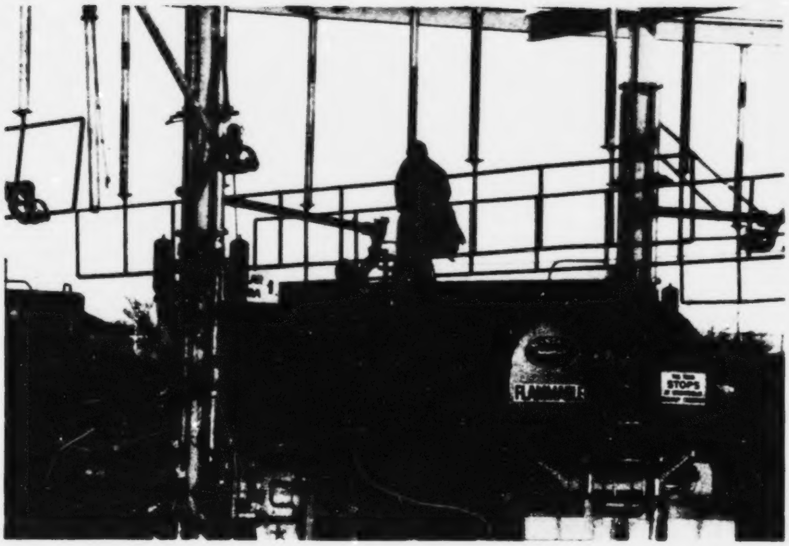


FIGURE 2.18 TRUCK LOADING RACK

fill pipe bonded to the tanks before any transfer commences.

Trucks that arrive with dirty tanks must flush them clean before taking receipt of products that differ from the previous payload, to prevent contamination. Terminal distribution areas normally provide tank washing facilities equipped with interceptors coupled with separators to prevent pollution.

It is the driver of the truck who usually loads his vehicle. Plant personnel are usually involved with rail tank car loading.

Once the driver has gained access to the top of his vehicle he removes the hatch covers, and then by means of either a hose or loading arm that allows the fill pipe to touch the bottom of the tank compartment, commences loading. Many of the modern loading installations dispense product through automatic preset meters that are equipped with an automatic shutdown once the desired volume has been transferred. However, most facilities still rely on manual control.

The normal procedure for filling is for an operator to open a spring loaded valve on the loading arm or above the hose, allowing discharge through the fill pipe. The operator must hold the valve open for flow to occur thereby making it necessary for him to be present and thus monitor the operation, to ensure that overfill conditions do not develop. Drivers have, however, been known to jam the valves open to avoid holding them in that position, creating a potential for overflow, particularly if they should leave the vehicle unattended.

Should an overflow occur, a driver can activate an emergency stop wire that will isolate that bay from the system by closing down the associated valves. Failing that, an emergency stop button can be depressed, shutting down power to the entire operation.

Levels are usually inspected visually with rods and meters.

Rail tank cars are normally filled either to some pre-set tank level with the volume necessary to reach that point displayed on the outside of the tank, or metered to a predetermined volume via automatic gauges.

(b) Bottom Loading

The bottom loading operation is not commonly used since most distribution docks are not equipped for it. The process is a float actuated automated system that is designed to shut down once pre-metered levels are reached. Since direct visual contact is no longer possible to regulate levels, a total reliance on the automated system is necessary. The automatic shutdown devices, however, have been known to fail, particularly after implementation of the system, and therefore emergency shutdown devices must be provided in the event of such a failure.

2.5.3 Water

Crude is transferred to Canadian and American destinations via crude carriers that range in size from 35,000 DWT through VLCC's (very large crude carriers) with a tonnage range from 100,000 DWT to 300,000 DWT, to moder ULCC's (ultra large crude carriers) with sizes in excess of 300,000 DWT.

Marine terminals capable of handling such large carriers and efficiently transferring their cargos to onshore bulk storage facilities, were designed and constructed. The cargo transfer operation undertaken while the carrier is at berth is an exacting procedure that requires precision, meticulous care, and teamwork between ship and shore personnel.

The cargo transfer operation associated with marine terminals may be subdivided into the following five phases:

(a) Preparation for Docking

Preparation for delivery includes transmission of information betwen applicable ship officers and shore personnel.

(b) Transfer Preparations at Berth

Once the carrier has berthed at either a single point mooring (SPM), single buoy mooring (SBM), or jetty, terminal representatives and ship's officers meet to coordinate the discharge operations. Concurrently deck officers make necessary preparations aboard the vessel that include cementing in deck scuppers, displaying warning signals, securing tank hatches, latching and sealing openings into the ship's superstructure, aligning and securing all hose flange connections, priming the pumps, removing lashings from cargo tank gate valve handwheels, and securing sea valves.

Ullages are measured and cargos are inspected before the unloading procedure begins.

(c) Cargo Transfer

Transfer operations involving product tankers are normally more arduous to perform than transfers from crude vessels resulting principally from the nature of the products handled and from the problems surrounding their segregation.

Once the appropriate safety checks have been completed to the satisfaction of ship's officers and terminal representatives, the signal is given to commence discharge. The rate of discharge is initially quite slow with the pumps brought up to the optimal speed in a regulated manner allowing deck personnel to check for leaks or other system malfunctions. Modern tankers have the capability of drawing cargo through common suction lines or from each tank individually to control stability.

Inert gas is normally pumped into the cargo tanks as discharging takes place to ensure that oxygen levels in the tank are kept well below 10%.

After the transfer is completed the pumps are stopped and the hose and manifold flanges are blanked. Drip pans are installed to ensure that leakage is contained.

(d) Ballasting

Ballasting commences by starting the pumps then opening the sea valves allowing water to enter the vessel into either the empty cargo tanks or into the segregated ballast tanks.

(e) Preparation for Sea

Finally, tanks are secured by lashing the handwheels on the control valves, P/V (pressure/vacuum) systems are checked, ullage ports are secured, equipment is properly stored, pilot tugs are deployed, and the vessel prepares for sea.

2.6 Accident Events

2.6.1 General Description of Accident Types

Accidents that result in the spills of petroleum products at major bulk storage terminals can be attributed to one, all or any combination of the following occurrences:

(a) Design error.

(b) Operator error.

(c) Equipment failure.

(d) Other.

Because of the relatively high significance of fires and explosions and the associated quantification of information available in the literature, fire/explosion accidents are described separately in Subsection 2.6.6.

2.6.2 Design Error

The general design function includes plant layout, location, tank layout, dikes, foundations, drainage, foam systems, water supplies, barricade, security arrangements, and other considerations [37, 100]. Specific equipment design is considered to constitute a component of equipment reliability.

In terms of accident potential, significant aspects of plant design may be described as follows:

(a) Foundation Analysis

(i) Assessment of Soil Conditions

Porous or permeable soil conditions within tank compounds must be given special conditions due to difficulties in detecting and successfully countering spills that might occur.

(ii) Foundation Design

Inadequate selection of foundation type or oversights in design with respect to prevailing soil conditions could lead to disparate settlement that often results in shell failure.

(b) Plant Layout

(i) Site Topography

Site topography is an important criterion for establishing safety requirements. Storage vessels located on hillsides near bodies of water, as is the case in many marine installations, must make special consideration for dikes. Terminals near bodies of water, populated areas and parks, wildlife reserves, or other sensitive environments required special design considerations.

(ii) Security

A reliable plant security system, including alarms, fencing, lighting, patrols, limited access, etc. should be developed to prevent acts of vandalism or sabotage.

(iii) Barricades

Pipework crossing or next to roadway must be protected against vehicle damage. Signs should be clearly posted marking routes--and limiting speeds.

(iv) Identification

Tanks, valves, and piping, should be clearly labelled.

(c) Tank Selection and Design

Although design is intrinsic in the costs of all equipment, with the plant designers being principally responsible for selection based on performance, adaptation, and other operational constraints, vessel design is isolated and analyzed separately due to its relative importance with respect to spill events.

(i) Material Selection

A plant designer must specify the types of products that are expected to be stored to ensure that suitable tank material is selected.

(ii) Type of Tank

The selection of tank type is reflected by the product handled, and therefore the designer must carefully balance use, safety, and economic constraints in determining which type or combination of types would be most suitable.

(iii) Roof

Choice of the type of floating pan or deck requiring attention to the construction material to ensure that governing standards are met. Flame spread ratings, density, compressible yield strength, shear strength, water vapour transmission, and porosity are all elements that must be carefully examined. Roof supports, bleeder vents, manways, anti-rotational devices, and all other associated hardward must be inspected and approved.

(iv) Design Inspection

The structural integrity of the storage vessels must be approved by the design engineer who ensures that required codes and standards are met. Proper bottom, weld, shell, and joint design are of paramount importance for safe efficient operation.

(d) Pipework

It is necessary to ensure that pipes are properly sized and that the material selected is suitable for required, temperature and location constraints, compatible with the product transmitted, and capable of withstanding predicted surge pressures. The pipe should meet governing codes.

(e) Equipment Selection

(i) Communication system

A suitable communication system must be provided to blanket the entire facility to ensure that information is conveyed both quickly and efficiently. Interpersonnel communciation is also vitally important to operational effectiveness.

(ii) Gauging Equipment

Designers must select appropriate gauging equipment meeting governing safety standards with respect to static dissipation, sparking, and electrical safety.

(iii) Alarms

Designers are responsible for the selection of high level alarms and decisions concerning redundant safety features.

(iv) Other Equipment

The designer must select the equipment that would be most suitable for the function for which it is required in terms of performance, maintainability, and reliability. The designer must also be aware of similar hardware in service elsewhere to evaluate performance and to help expedite repairs.

(f) Other

Although a designer must endeavour to minimize risks to the plant's employees, he must eliminate all known risks to the public as far as possible. The former accepts the risks of his profession whereas the public is unconsenting.

2.6.3 Operator Error

Operator errors include both operating and maintenance related errors that together constitute the principal source of spill accidents. Operator activities are associated primarily with the movement of product from one terminus to another, whereas maintenance activities are aimed at ascertaining that the hardware functions adequately. In operator dependent systems human error occurs despite significant improvements in technology and engineering design [3, 15, 18, 37, 80, 97, 100, 107, 122, 14].

The following list identifies some of the operator errors that can be associated with the bulk transfer operation:

(a) Manual gauging to check calibration on the automatic gauges not regularly performed.

(b) Operator calculates charging time using an incorrect feed rate, which could result in overflow, particularly if the operator leaves the station during filling.

(c) Poor communication could result in mixing of products within a tank should interfaces unexpectedly be encountered in a major feeder line, or overflow if the wrong tank is charged. In certain situations written procedures should be employed.

(d) An operator that does not report falling tank levels may be responsible for allowing petroleum to leak through the tank bottom.

(e) Contamination may result if water drawn from the tank is not channelled through an oil/water separator, but allowed to run into the ground.

(f) Operators that do not operate hardware within its specified parameters enhance failure and spill potential.

(g) Tankage feed rates not regulated to levels that will prevent static problems.

(h) Assigning new personnel to the crew would disrupt functioning through poor coordination, particularly in crisis situations.

The execution of a good preventive maintenance program is a vital measure necessary in minimizing unexpected equipment failures that could otherwise lead to serious spills and lengthy downtimes. Inspections must be methodically executed, keeping accurate up-to-date records on the condition of equipment to help coordinate maintenance, repair, and operation activities. Furthermore, inventories of emergency repair equipment should be supported. The following list includes maintenance related preventive procedures to minimize spills:

(a) Small leaks and signs of corrosion must be immediately attended to because failure to do so could cause serious problems that could lead to environmental contamination and large associated costs.

(b) Hydrostatic testing of tanks and other vessels together with an examination of pipes, valves, and fittings subjected to spurious levels of pressure, serve to reveal weaknesses and potential areas of failure. Simulating spill situations allow operators the opportunity to evaluate their fail-safe systems. Nondestructive shell thickness testing (ultrasonic analysis) and visual inspection of tanks will also reveal leakage.

(c) Abrasion occurring around the pipe supports should be checked.

(d) Flame arrestors must be cleaned regularly.

(e) Vents must be kept free from obstructions because obstructing vents could cause tank collapse. Examples of these incidents include: covering vents to prevent dust intrusion into the tanks while pressure/vacuum hardware is being maintained. For example, vents near walkways may be covered to curtail malodorous tank emissions, allowing birds to construct nests in the vents, and not preventing ice formation that could clog vents.

(f) The quality of maintenance is often affected by the speed of repair.

(g) Proper lubrication of moving parts to prevent premature equipment failures that otherwise would increase spill potentials.

(h) Clearance certificates and work permits must be carried by all contractors for approved work within the property.

These permits could be color coded for easy identification. British Petroleum for example issues cold work, not work excavation and entry permits. Work on electrical equipment is regulated by a different system. Figure 2.19 shows a contract welder working on a tank.

(i) Fail safe equipment, alarms, trips, and other control hardware and instrumentation should be regularly checked.

(j) Dry runs of systems that have undergone repair or service and new systems supplemented into the existing ones, should be undertaken to uncover incompatibilities that could lead to critical real-time failures.

(k) Ensure that components are not damaged during handling.

(l) Provide human supervision to ensure that components are not installed out of sequence.

2.6.4 Equipment Failure

Conformity to existing codes and standards is not an absolute defense against the failure of hardward, due to latent defects that may result from both mutable material properties and fabrication processes. It is also quite obvious that cost and quality and performance of equipment and replacement parts tend to parallel each other. Inexpensive replacement parts in expensive equipment reduces the performance capabilities of the whole to the level of the cheapest component, and although an initial saving is realized, higher maintenance costs, spill potential, and frequency of replacement defeats any advantage in the long run.

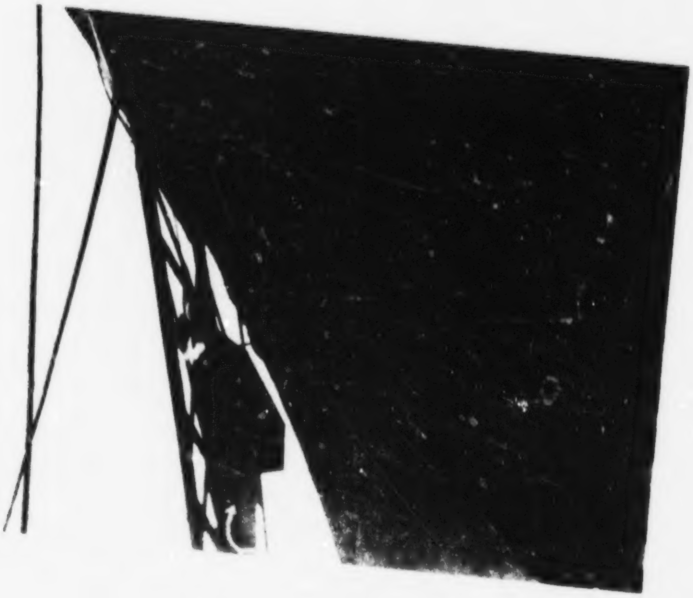


FIGURE 2.19 CONTRACT WELDER

The following include some common areas of failure [3, 18, 20, 37, 8, 88, 100, 103].

(a) Welds

Surfaces that have not been properly cleaned of all scale, grease, slag, or oxides, or prepared to ensure a sound metal base for welding, could lower the quality of the weld. Welding undertaken during adverse weather conditions or outside the permissible range of the base metal temperature also provides a cause for failure. Other weld related defects that could lead to failure include: plates not matching within tolerances; incomplete joint penetration; or undercuts, overlaps, ridges or valleys within the length of weld.

(b) Pressure or Vacuum Relief Devices

Deficiencies in spring and weight loaded devices are significantly greater than in pilot operated relief valves, because the former rely effectually on operating overpressure to function. Since most vessels operate under relatively low pressures, the uplift forces acting on the devices may not be high enough to overcome the resistance imposed through the friction developed by moving parts or by the possibility of sticking. These valves may, furthermore, limit the flow since the forces on the valve springs tend to increase as it opens.

(c) Fittings

Fittings and gaskets have a tendency to wear, and as a result must undergo careful inspection which, together with a good replacement program, should eliminate most related spills.

(d) Worn Valves

Packings around gate valve stems often become loose through wear and tend to leak if not repaired. Check valves and butterfly valves are vulnerable to sticking. Others have been derelict in closing unexpectedly against the flow creating dangerous surge pressures.

(e) Tank Bottoms

Tank bottoms are very susceptible to corrosion and leaks that result are more difficult to detect than corrosion occurring elsewhere in the tank. Properly lining corroded tanks with fibreglass or epoxy will suppress further corrosion by filling in small pits or crevices.

(f) Flow Rate Indicators

Jamming or sticking of flow rate indicators could lead to errors in estimating fill time on tanks that if unattended could lead to overflow.

(g) "Frangible" Roof Welds

A frangible roof is designed to fail along roof-shell welds should uncontrolled overpressurization of the tank occur, thereby preventing damage to the shell or base; consequently, failure of this weld to yield as designed could cause rupture and subsequent product loss.

2.6.5 Other Hazards

The following includes a number of other events that can be considered extrinsic factors that are not possible to control [3, 35].

(a) Environmental limit transgressions such as hurricanes, floods, tornadoes, earthquakes, and tsunami.

(b) Violent acts including arson, sabotage, and acts of man or civil unrest.

(c) Unknown causes in cases where leaks are identified but no apparent causal mechanism can be associated with them.

2.6.6 Fire and Explosion

There are fewer incidents of fire or explosion in terminal storage operations than other accidents that result in petroleum losses, probably due to the current high level of fire and explosion preventive cost.

Burn time is an integral element in assessing fire accident cost, and therefore design, operator, and equipment considerations in fighting a fire are as important as measures taken for fire prevention.

The following are items relevant to the prevention and control of fire/explosion accidents in bulk plants [77, 97, 164]:

(a) Provide water, deluge, and/or foam protection system (Figures 2.20 and 2.21).

(b) Careful consideration of extinguishing agents and injection systems must be given to adequately combat tank fires (Figure 2.22).

(c) Flexibility in fire control is required, foam trucks should be contemplated. A suitable selection of model (combined agent, triple agent, standard, and elevated boom) should be considered contingent upon requirements, and hazards involved.

(d) Foam systems require a compatible water supply together with sufficient pressures to generate foam.

(e) Designers must ensure that the governing fire standards are met with respect to layout of fire equipment.

(f) Fire water pumps must be maintained to ensure that water will be available if required.

(g) It is essential that more than one closed water supply system is available in the event that one fails.

(h) Main fire monitors (Figure 2.23) should have the provision to be activated at remote locations.

(i) Operators must be familiar with the operation and location of all fire fighting equipment in the property.

(j) Different methods of extinguishment are necessarily contingent upon the nature of the burning product. Consequently, hydrants should be coded to permit rapid identification.

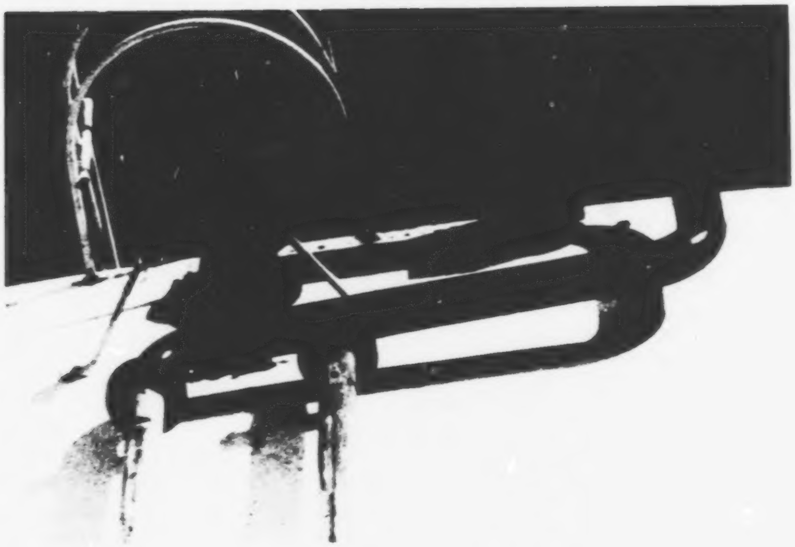


FIGURE 2.20 FOAMITE LINES FEEDING INTO TOP OF TANK

FIGURE 2.21 FOAMITE HYDRANT

FIGURE 2.22 CHEMICAL HYDRANT

FIGURE 2.23 FIRE WATER MONITOR

(k) The plant must be designed for adequate tank separation to make certain that any tank explosion or fire that might occur is isolated from other tanks to avoid setting off a chain reaction (Figure 2.24).

Vigilance must also be maintained to control sources of ignition including the following:

(a) Smoking - Allowed only in designated areas (Figure 2.25).

(b) Static electricity - Generated through excessive flow rates, or the use of metal sounding or sampling rods, and metal sampling apparatus.

(c) Spontaneous combustion - All oil rags and rubbish should be deposited into waste receptacles.

(d) Electrical apparatus - Non-approved electrical apparatus must not be utilized in areas designated as hazardous (Figure 2.26).

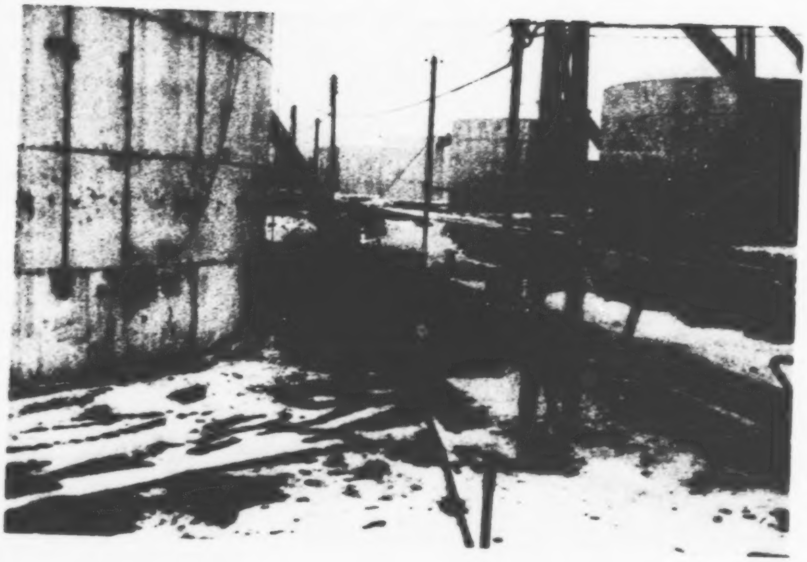


FIGURE 2.24 PUMP, LINES, AND STORAGE TANK LOCATED IN DIKE AREAS

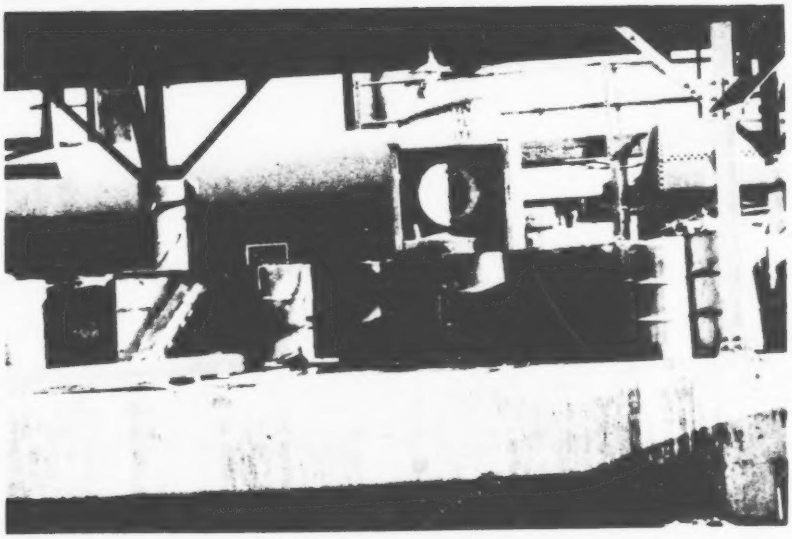


FIGURE 2.25 SMOKING, A SOURCE OF IGNITION, IS STRICTLY PROHIBITED

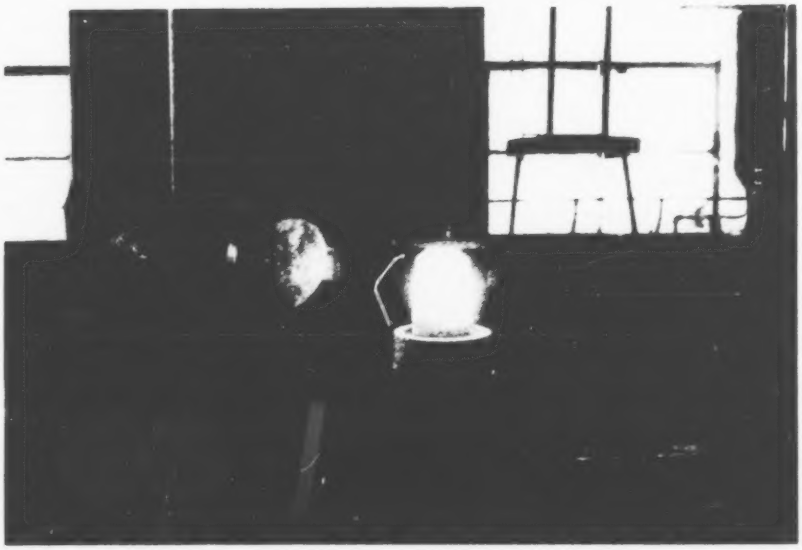


FIGURE 2.26 SAFELIGHT

CHAPTER 3

ANALYSIS

3.1 General Description of Analysis

Previous work in risk analysis of hydrocarbon facilities by the authors [12, 13, 14] has included only the determination of risk, or accident probability, and risk expectation, or expected accident volume per unit time. Such analyses, accordingly, have concerned themselves primarily with the prediction of event-space-time configurations, without considering cost and consequence. The methodology utilized in such investigations as well as others [86] is that of fault trees, a well proven direct probablilistic nonlinear network technique historically evolved through the need to analyze failure probabilities of systems without history [12, 13, 14].

For the current work, fault trees will again be utilized as a basis for evaluating accident risk. In order to evaluate spill expectations, cost relationships, and optimize cost, the basic fault tree concept was extended to develop expectation and cost trees. Optimatization was achieved through superimposition of a direct nonlinear optimization search technique on the cost tree.

In the balance of this chapter, accordingly, the evolution and structure of the analysis will be presented under the following headings:

(a) Fault Trees.

(b) Expectation Trees.

(c) Cost Trees.

(d) Optimization.

Some specific application notes will be made in relation to definition of cost tree inputs and cost jurisdictions.

3.2 Fault Trees

A fault tree network is a probabilistic logic network combining all possible sequences leading to an event which is under study. In this particular case the probabilistic analysis is compounded with a cost analysis in an attempt to achieve an association between the probabilities of accidents that lead to petroleum spills, and the usual operating and capital expenditures incurred by an operating bulk storage terminal.

In fault tree development, the lowest level reached in the fault tree is defined as a basic event. Clearly, all basic events considered in the fault tree are relevant to the occurrence of the higher event in the hierarchy of events. In the case of systems for which a long operating history is not available it is not possible to utilize statistical methods to predict their overall performance. However, it is generally possible to obtain statistical information on the performance of similar components or subsystems where the historical information is available. Essentially, the fault tree approach utilizes as statistical or probabilistic inputs information on basic events which, although not evaluated within the context of the present system, are sufficiently similar to that they can serve as potential inputs to the system under consideration.

One might consider all possible events as basic events. This is, however, unrealistic. It is not possible to decide in a realistic way whether an event has a significant probability of influencing the top supreme resultant event for all possible events. For example, if we consider the probability that Mr. X, where X is a random name, has a car accident in Squamish, B.C., then this event would at first consideration seem totally irrelevant to the top supreme resultant event. However, if we consider the possibility that Mr. X may have been the superintendent for the plant under consideration, and would in a future emergency execute the proper action sequence that prevented an oil spill, and that his replacement, Mr. Y, will fail to do so--then it is a significant basic event. Thus, virtually any fault tree generated will not encompass all factors and no real fault tree can manage to do so within feasible numberical limits compatible with work objectives. Accordingly, the level of basic event chosen was that which, in the reasoned opinion of the writers, collaborators, and others is probabilistically significant within the analysis under consideration. Systematic spotchecks indicate that, in fact, there appear to be no other basic events that influence the top event with the same or higher orders of magnitude than those chosen in the fault trees given herein.

The fault tree was evolved using a top-down recursive procedure. Table 3.1 identifies the hierarchy of events for a typical fault tree [13].

Starting with the top supreme resultant event, the constituent main resultant events were identified. The following recursive procedure was utilized for the lower levels:

TABLE 3.1

HIERARCHY OF EVENTS

Class	Description
1	Supreme Resultant Events
2	Main Resultant Events
3	Resultant Events
4	Sub-resultant Events
5	Postbasic Event
6	Basic Event

(a) Given an event, X_n, what are the events causing X_n?

(b) The events causing X_n are either $X_{n-1}^{(1)}$ and $X_{n-1}^{(2)}$...and $X_{n-1}^{(k)}$ or $X_{n-1}^{(1)}$ or $X_{n-1}^{(2)}$ or ... or $X_{n-1}^{(k)}$, generating "and" gate or an "or" gate, respectively, or their combination.

In the above manner, it is possible to recursively refine the event levels to a more and more basic set of events. Naturally, the level of refinement can be arbitrarily fine. Due to scope, time, economic, data, and other constraints, the level of refinement must be limited to a relatively coarse one.

Table 3.2 gives the main logic symbols utilized in the fault trees herein. Figure 3.1 shows the overall structure of the fault and cost trees utilized for the current study.

In the current study the hierarchy of probability events is limited by both the cost analysis and the difficulty in assigning probabilities to all the various elements of the events. Scope, time, and economic constraints also limit the level of refinement. The uppermost events in the bulk plant probability hierarchy therefore include the six major accident events that result in petroleum spills in the terminal operation, as follows:

(a) Tank overflow.

(b) Tank leakage.

(c) Tank rupture.

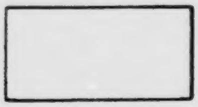
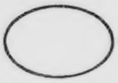
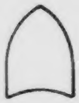
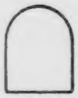
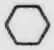
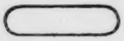
(d) Ancillary equipment leak.

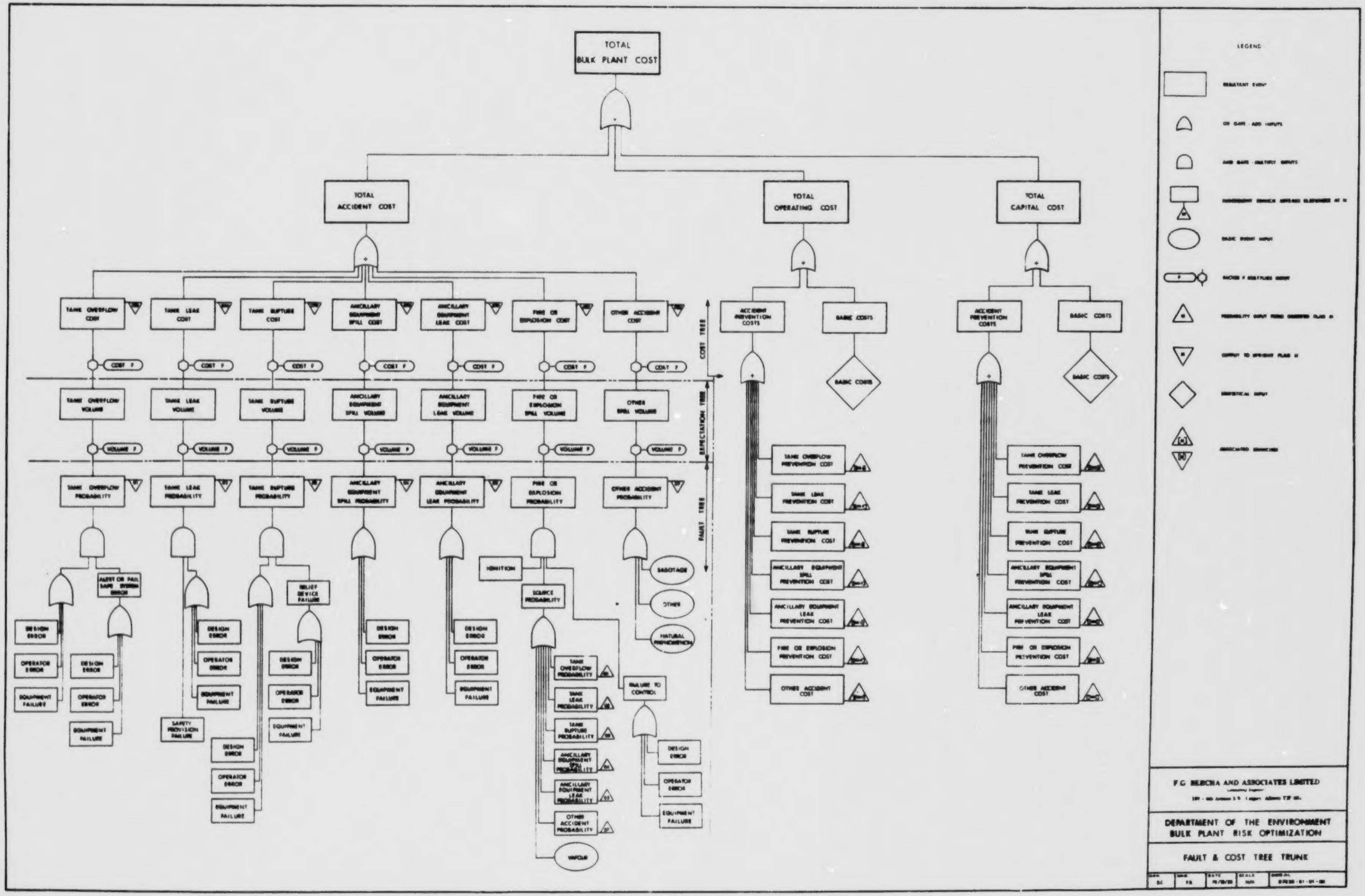
(e) Ancillary equipment spill.

(f) Other.

TABLE 3.2

GRAPHIC LOGIC LEGEND

Symbol	Description
	Postbasic or higher event
	Basic Event
	Either or
	And
	Conditional
	Conditional event


TOTAL BULK PLANT COST
TOTAL ACCIDENT COST
TOTAL OPERATING COST
TOTAL CAPITAL COST
TANK OVERFLOW COST
TANK LEAK COST
TANK RUPTURE COST
ANCILLARY EQUIPMENT SPILL COST
ANCILLARY EQUIPMENT LEAK COST
FIRE OR EXPLOSION COST
OTHER ACCIDENT COST
COST F
TANK OVERFLOW VOLUME
TANK LEAK VOLUME
TANK RUPTURE VOLUME
ANCILLARY EQUIPMENT SPILL VOLUME
ANCILLARY EQUIPMENT LEAK VOLUME
FIRE OR EXPLOSION SPILL VOLUME
OTHER SPILL VOLUME
VOLUME F
TANK OVERFLOW PROBABILITY
TANK LEAK PROBABILITY
TANK RUPTURE PROBABILITY
ANCILLARY EQUIPMENT SPILL PROBABILITY
ANCILLARY EQUIPMENT LEAK PROBABILITY
FIRE OR EXPLOSION PROBABILITY
OTHER ACCIDENT PROBABILITY
COST TREE
EXPECTATION TREE
FAULT TREE
ALERT OR FAIL SAFE SYSTEM ERROR
RELIEF DEVICE FAILURE
SAFETY PROVISION FAILURE
DESIGN ERROR
OPERATOR ERROR
EQUIPMENT FAILURE
IGNITION
SOURCE PROBABILITY
FAILURE TO CONTROL
VAPOUR
SABOTAGE
OTHER
NATURAL PHENOMENON
ACCIDENT PREVENTION COSTS
BASIC COSTS
TANK OVERFLOW PREVENTION COST
TANK LEAK PREVENTION COST
TANK RUPTURE PREVENTION COST
ANCILLARY EQUIPMENT SPILL PREVENTION COST
ANCILLARY EQUIPMENT LEAK PREVENTION COST
FIRE OR EXPLOSION PREVENTION COST
OTHER ACCIDENT COST
LEGEND

F.G. BERCHA AND ASSOCIATES LIMITED

DEPARTMENT OF THE ENVIRONMENT
BULK PLANT RISK OPTIMIZATION

FAULT & COST TREE TRUNK

Fire and/or explosion is the seventh major accident event, listed separately, because it need not necessarily result in spill but rather be the consequence of one. Figure 3.1 shows the upper level of the bulk plant fault tree. Figure 3.2 represents the tank overflow probability branch which will serve for purposes of illustration. Proceeding down the tree from the "Tank Overflow" event, which shall be considered as the supreme event, the next link in the chain of events must be the criterion for the supreme event to occur.

Tank overflow will occur if:

(a) A failure in the tank filling operation occurs allowing the product to approach "spill" status.

(b) The fail-safe provisions fail.

Consider that a failure in the tank filling operation occurs allowing the product to approach spill status. This event now becomes the uppermost event for a new series of events that satisfy it.

Therefore, a failure in the tank filling operation occurs allowing the product to approach spill status because of a design error, or a human error, or an equipment failure.

This is to say that any one of the above three events will cause a failure in the tank filling operation. However, these events do not necessarily imply that an overflow will occur, but rather, that the potential for an overflow exists. For example, an operator who overestimates filling time changing an empty tank to one-half vessel capacity will be less likely to overflow the tank than the operator who overestimates filling a half-full tank to capacity. The consequences of each failure are therefore different and only a percentage of these

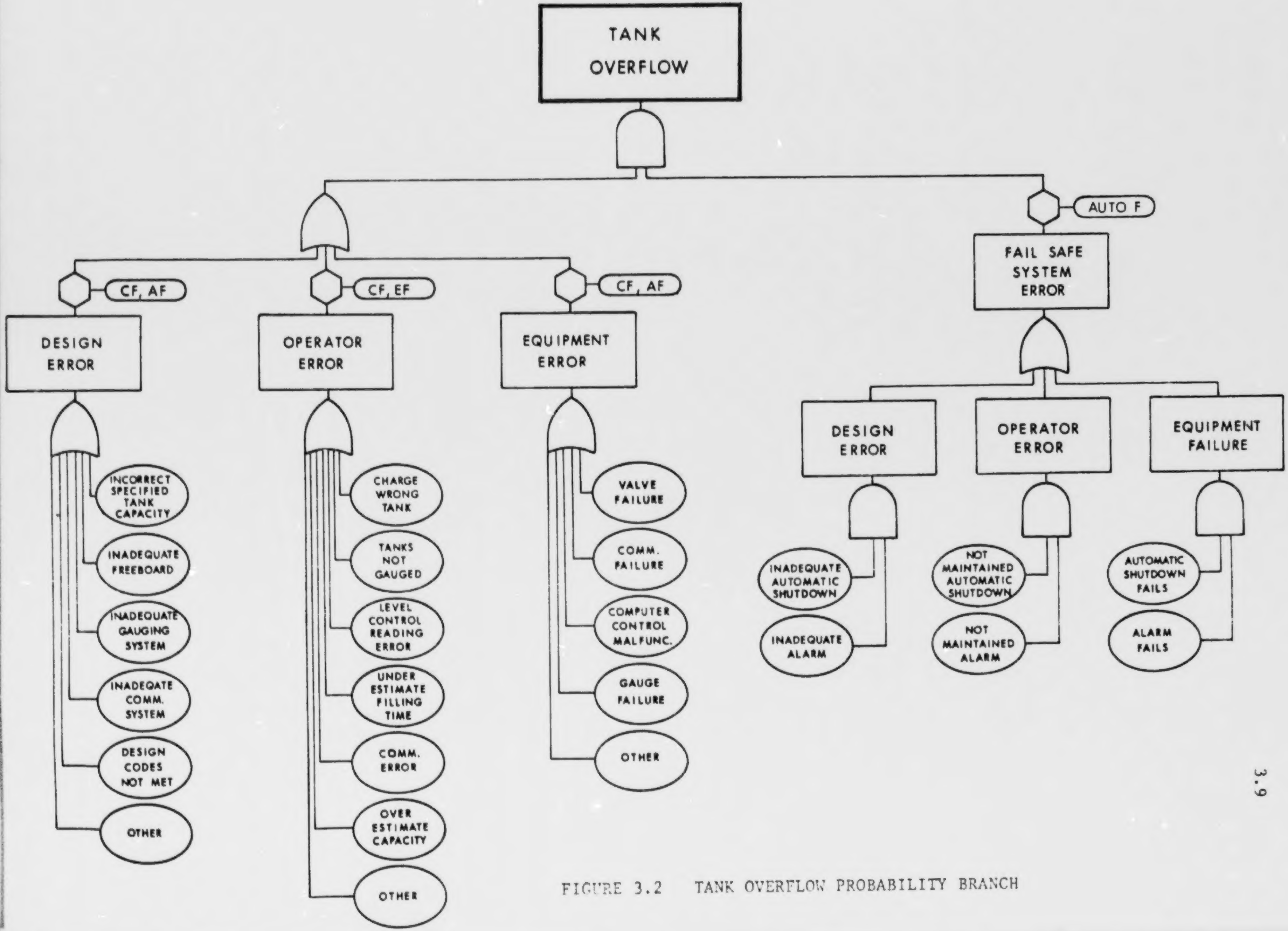


FIGURE 3.2 TANK OVERFLOW PROBABILITY BRANCH

errors will result in actual spill, hence the implementation of the consequence factor, (CF), which acts as a cover "and" gate. It would have furthermore been impractical to try to assign a CF to every event and as a result consequence factors were applied at the design error, operator error, and equipment failure level. Suppose the consequence factor, CF = 0.2. This implies that an average of two out of every ten operator failures occurring during tank charging will cause the product to approach spill status. Such a filter factor was also used in the study [13] on blowouts.

Failure in the tank filling operation may now occur allowing the product to approach spill status, because of:

(a) A design error modulated by CF, or,

(b) A human error modulated by CF, or,

(c) An equipment failure modulated by CF.

Consider now that the fail-safe provisions fail.

The fail-safe provisions include high level alarms and automatic shutdowns. Many of the older tank farms are not equipped with either of these devices, and as a result would have have this chain of events as input into the fault tree. The fail-safe provisions fail event is subdivided into:

(a) Design error, or,

(b) Human error, or,

(c) Equipment failure,

each in turn acting as the uppermost event for chains of basic events.

If the situation has developed to the point where the fail-safe system is to be engaged, one can assume the problem has reached a critical level, and therefore any failure of the fail-safe system would culminate in error. For this reason, no consequence factors, CF, are introduced into these branches.

3.3 Expectation Trees

Figure 3.3 shows the relationship between the probability tree and the expectation tree within the accident cost branch of the fault tree network.

The expectation factor, (EXPF), is defined as the expected amount of product spilled in one year given that a spill occurs during each filling operation; that is, when the probability of spill is 1. The expectation factor is calculated by either of the following two relationships contingent upon the type of accident considered:

(a) For tank overflow, tank rupture, and tank leakage:

$$EXPF = VSPI * NOP * NTFO, \tag{3.1a}$$

where VSPI is the average volume spilled per incident, NOP is the average number of operations per year, and NTFO is the average number of tanks filled per operation.

(b) For ancillary equipment leak, ancillary equipment spill, and other:

$$EXPF = VSPI * NOP. \tag{3.1b}$$

For the fire/explosion subtree the expectation factor is set to 1, since it is assumed that all product is lost (consumed in this type of accident).

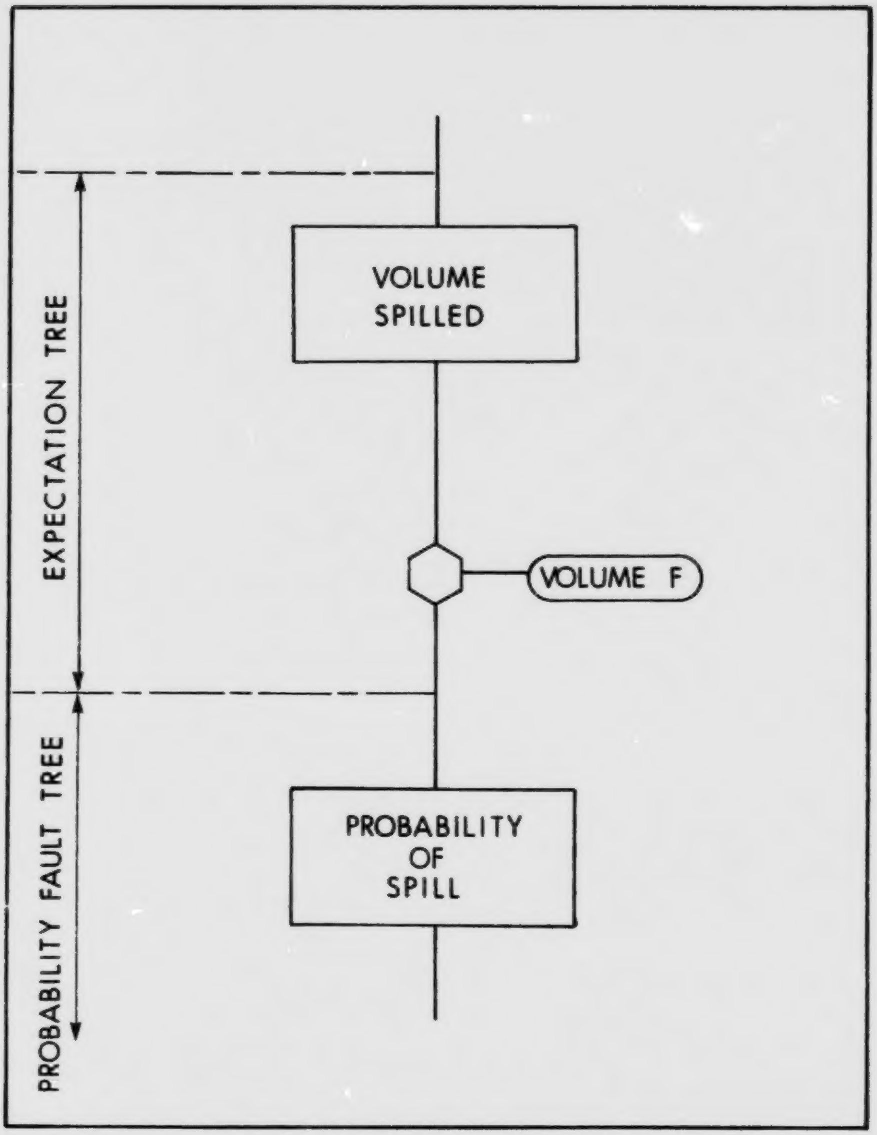


FIGURE 3.3 EXPECTATION RELATIONSHIP TO PROBABILITY

3.4 Cost Trees

3.4.1 General Concept of Cost Trees

The connection between cost and expectation trees is obtained through application of a spill cost factor. Evaluation of the spill cost factor, the effective cost per unit volume of spill, must be carried out within the socioecological constraints of plant operation, and includes a variety of parameters such as product, clean-up, penalty, environmental damage, resource, industry, publicity, and other costs. Clearly, evaluation of such factors cannot be done generally; but must be carried out for each specific or at least typical plant. For general cost items, those associated with plant capital and operating costs may be developed separately from accident costs and are generally valid for a representative range of plant types.

In the balance of this section, a discussion on cost trees under the heading of accident cost trees, and capital and operation cost trees will be presented.

3.4.2 Accident Cost Trees

The accident cost tree presented in Figure 3.4 depicts the relationship of costs associated with a spill incident involving bulk plant storage. Cost calculation involves multiplication of the expected volume of product spilled by the unit costs associated with the spill, COSTF, and finally dividing by the annual throughput in barrels to compute the expected annual accident cost per barrel handled.

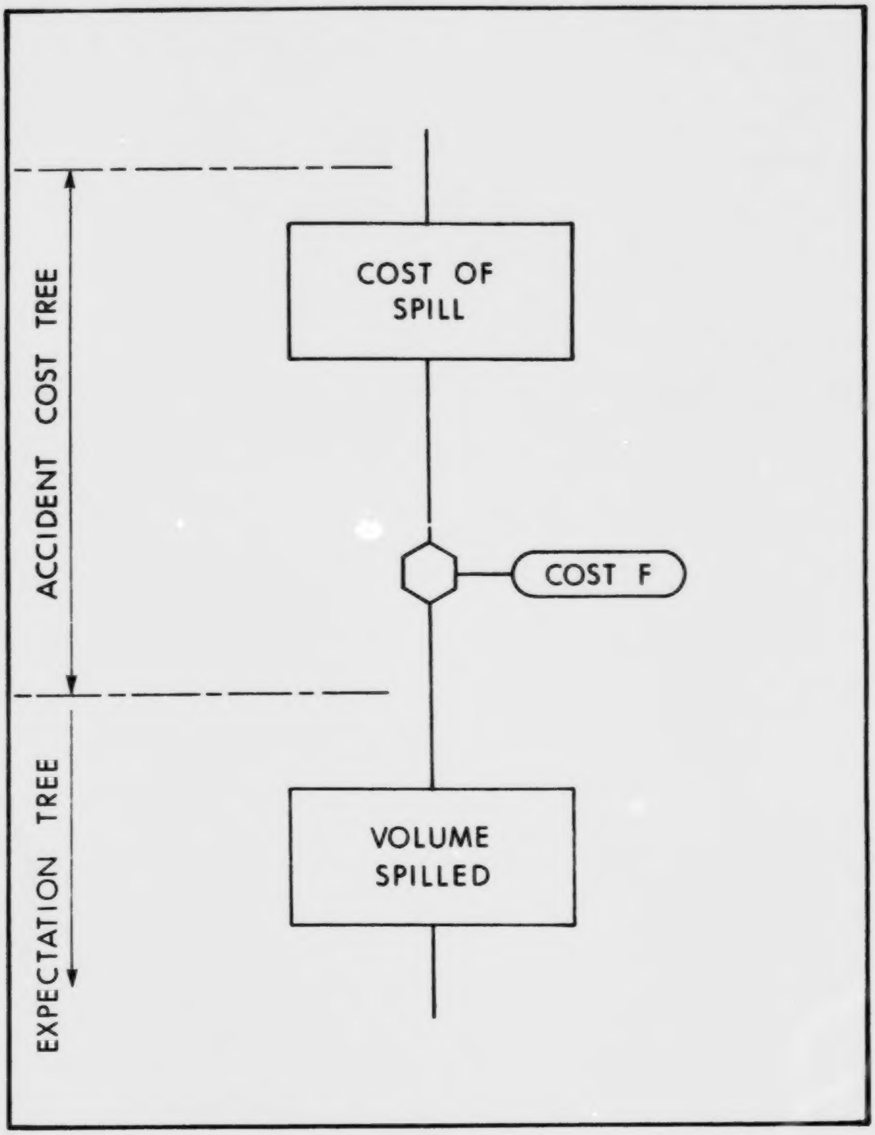


FIGURE 3.4 ACCIDENT COST RELATIONSHIP TO EXPECTATION

Accordingly,

$$ACOST = \frac{AEXP * COSTF}{THRUPUT}. \qquad (3.3)$$

The liabilities identified with the clean-up operation include the physical clean-up costs, penalties, third party indemnity, and other administrative costs [21, 47, 69].

The cost incurred in the clean-up operation, COSTF, varies significantly from incident to incident, influenced by a number of factors that include:

(a) The size of the oil spill. (The per barrel cost decreases as the size of the spill increases.)

(b) The nature of the product spilled.

(c) The season during which the spill occurred.

(d) Weather.

(e) Wave height, in the case of harbour spills.

(f) Surface and subsurface soil conditions.

(g) The environment affected by the spill. (Spills on impermeable surfaces are easy to clean up whereas spills entering subsurface into acquifer are extremely difficult to handle.)

(h) The time elapsed between discovery of spill, notification, and response.

(i) The method of containment.

(j) The recovery method.

(k) Treatment and disposal procedures.

(l) The percentage of the spilled product that was recovered.

(m) The proximity of the spill to ecologically sensitive areas.

(n) Cause of spill. (Some causes may provide legal grounds for avoiding liability.)

(o) Source of spill. (Spills that result from design errors or equipment failures may lead to additional repair or replacement costs.)

The cost factor COSTF is therefore dependent on the above factors. The COSTF used in the program was arrived at by considering an average accident clean-up cost computed on the basis of representative spill facility and location data.

The cost factor may, for a particular facility, be computed as a function of its location, equipment and spill history.

3.4.3 Operating Cost Trees

Operating costs include the operating and maintenance costs that are incurred in the day-to-day operation of the plant [7, 117]. Such operating costs include the following:

(a) Operating and maintenance labour costs.

(b) Fuel required to run turbines and pumps, or to heat tanks.

(c) Consumable supplies.

(d) Insurance and property taxes.

(e) Stocks of repair material and replacement parts.

(f) Contracts awarded to outside contractors.

(g) Power and water bills.

(h) Grooming costs including painting tanks, planting trees, grounds keeping, etc.

(i) Miscellaneous costs including donations, fees, duties, etc.

For the purposes of the present analysis, the operating costs must be apportioned between accident prevention costs and other, "basic" costs. Apart from a few cost items such as fuel expenses and property taxes, most of the operating expenditures contribute to accident prevention to some degree. Judgement is required in assigning a portion of each category to accident prevention. For example, it would be reasonable to assign one-third of an operator's salary, and three-quarters of a maintenance man's to the prevention of accidents.

Having established the total operating accident prevention cost, it must now be further subdivided into accident prevention activities or events that correspond to the basic accident events. For example, closing the wrong valve is a basic accident event that could lead to a spill from ancillary equipment. The corresponding operating accident prevention event would be operator training. A training program would obviously encompass many aspects of the bulk plant operation, and training would be specified as the corrective measure for many of the basic operating accident prevention events. The problem then is the distribution of training costs to each of these events. The technique adopted here involves the analysis of typical training program curricula in order to determine the amount of class time that is relevant to each event. The instruction time spent on ancillary valves divided by the total length of the program and then multiplied by its total cost would yield an approximate training cost for valve operation. Not all of this training would be directed to accident prevention, however, and the cost must therefore judiciously be divided between accident prevention and normal training.

Records of operating costs must be obtained for a number of existing storage installations and then classified according to plant capacity, throughput, and location. These costs may be used as the basis for an estimate of the operating costs for any proposed bulk plant. If the level of operation of an existing facility is to be studied, then a history of that facility's operating basic and accident prevention costs would be the most appropriate basis for the analysis.

3.4.4 Capital Cost Trees

The Capital costs for the model are defined to be the cost of fixed assets. These include the costs associated with the following:

(a) Planning and feasibility studies.
(b) Architectural and engineering design.
(c) Land acquisition.
(d) Construction.
(e) Pre-operation allowance.
(f) Equipment purchase and installation.
(g) Contingency.
(h) Miscellaneous.

Depending on overall size of installation, tank sizes, location, products handled, throughputs, and other factors, the bulk plant capital costs will differ significantly throughout the industry [7].

The first step in determining capital costs is to calculate the cost of tankage which together with pipework constitutes approximately 75% of the total capital expenditure. From correspondence with storage tank manufacturers, the cost per barrel capacity erected of several types and sizes of low pressure tanks was obtained based on 1978 dollars and a Calgary location, as summarized in Table 3.3 while Figure 3.5 shows relative cost curves.

Costs for the supply and installation of internal floating decks are also provided based on per barrel tank capacities. Fixed roof tanks, open floating roof tanks, and fixed roof tanks with an internal floating deck comprise the three categories of tank considered. The fixed roof tank is least expensive relative to the remaining two types, with the open floating roof tanks being marginally more costly than the covered floating roof tank. If a profile of tank requirements is known in terms of quantity and related capacities for a proposed facility at a given point in time and at some established location, then the total erected tank costs can be accurately determined by multiplying tank capacities by their corresponding dollar per 'barrel stored' costs.

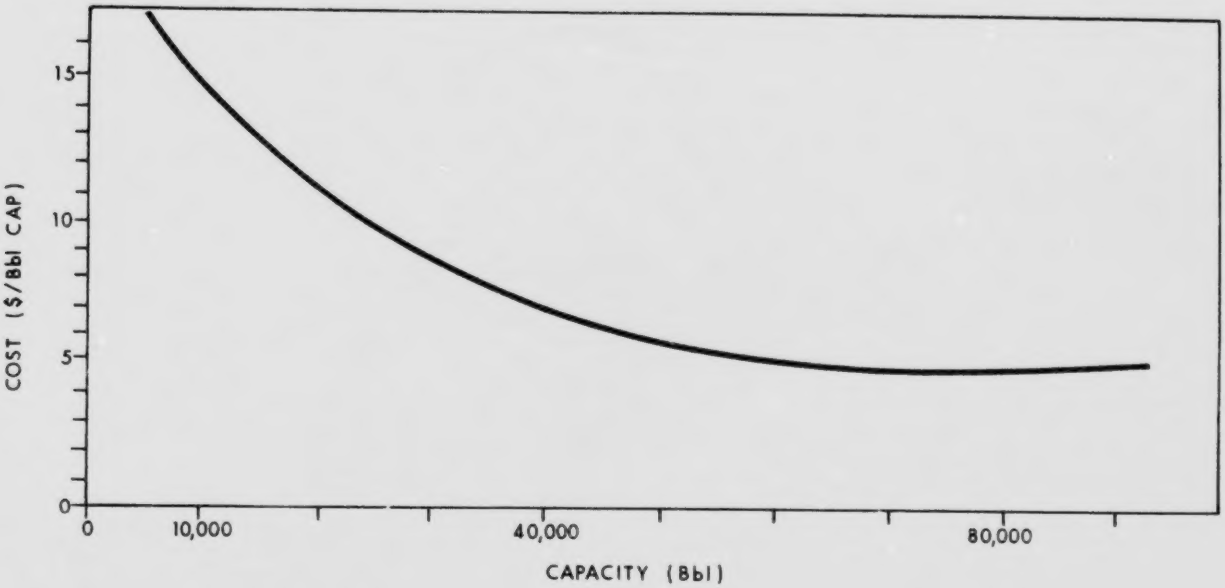
If only the aggregate capacity of a proposed terminal is settled without further refinement to specific tankage sizing, then an intermediate capacity tank should be selected for cost estimating. A 35,000 bbl capacity storage tank will be considered about average for an inland terminal, and 50,000 bbl average for an onshore marine facility.

TABLE 3.3

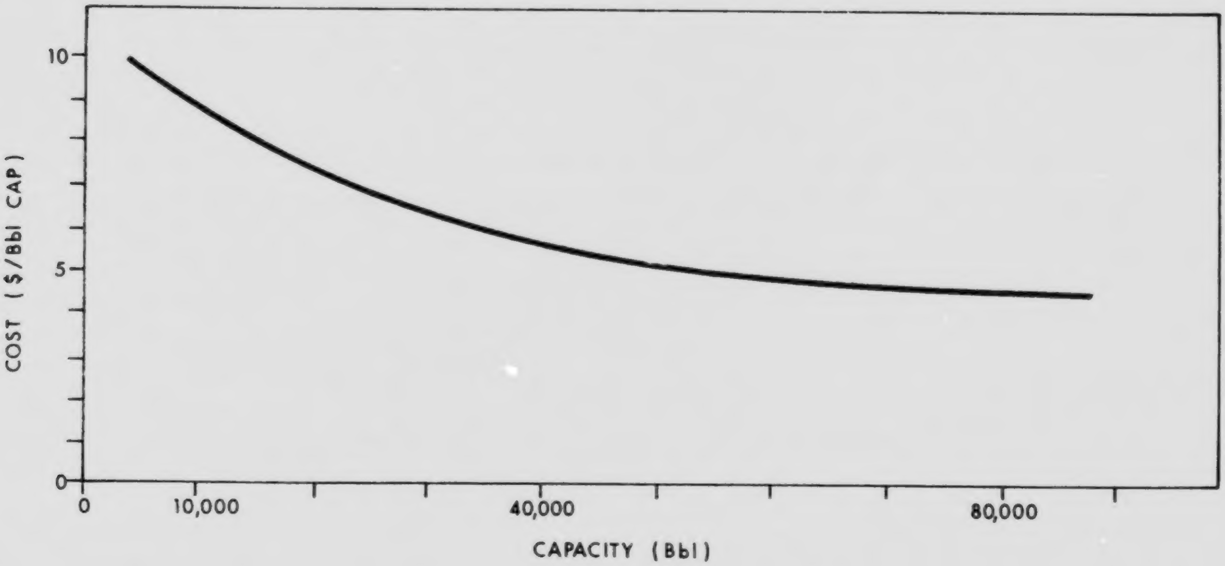
APPROXIMATE 1978 CALGARY COSTS
FOR ERECTED STORAGE VESSEL

(Type V) Floating Pan for Crude Storage	
10,000 bbl capacity	$15.00/bbl stored
40,000 bbl capacity	$ 7.00/bbl stored
80,000 bbl capacity	$ 5.50/bbl stored

Fixed Roof Vessels	
10,000 bbl capacity	$ 9.00/bbl stored
80,000 bbl capacity	$ 4.50/bbl stored



(a) Erected Costs for Type V Floating Pan Crude Oil Storage Tank
Calgary (1978)



(b) Erected Costs for Fixed Roof Tanks
Calgary (1978)

FIGURE 3.5 TANK COST CURVES

The erected costs of the tankage should include about 60% of the total capital cost. Consequently, an estimate of 1.6X the erected costs of the tankage would give an approximation of the overall capital expenditure. The remaining 40% consists of costs associated with land, foundations, pipework, pumps, gauges, fire control, dykes, buildings, fences, etc.

The capital cost is then amortized over 25 years at 10% interest to obtain the annual payments, which are then divided by the annual throughput to determine the capital cost per bbl of product handled.

Itemized costs must also be estimated for the land, buildings, and hardware that form the balance of the capital expenditure. Limited accessible published data exist on component, material, and land costs, primarily resulting from the mutability of the market with time and the regional disparities that exist between locations at the same point in time. Much of the available data are far too obsolete to be useful. One feasible method of accumulating meaningful rates would be through rigorous correspondence with equipment manufacturers and contractors, and even then many of these costs could vary since many contracts would normally go up for bid. This process, however, would be time consuming and upon its completion much of the infomration would again be outdated. Another more practical procedure would be to obtain detailed records of a recently contstructed bulk plant, with identifiable characteristics, and then to modify these costs for bulk plants with different throughputs and at various locations to give good cost approximations.

Once a reasonable cost base has been established, costs must be divided into normal capital costs necessary towards achieving the objective of the operation and capital accident prevention costs which allow the operations to function smoothly and safely.

This assessment can often be a formidable undertaking because no precise separation of objectives may exist.

For example, dykes, alarms, and fire equipment do not contribute towards the basic operation of the plant, other than the solace that they might indirectly offer an operator, who because of the presence of these devices, functions more effectively. On the other hand, items for aesthetic purposes like landscaping and paint, or signboards displaying the company's title, are wholly basic in that they have no accident prevention component. However, most of the items included in capital expenditure embrace both objectives to varying degrees. The thickness of a tank shell can be defined as that thickness of material necessary to just counteract both the pressures of the stored product and the forces of nature, plus the thickness added as a factor of safety.

3.5 Optimization Procedure

Once the base bulk plant scenario has been established, optimization and sensitivity analyses can be carried out to study the facility's current or proposed level of operation relative to some optimum economic rate based on functional relationships between operating accident prevention cost, accident cost, capital accident prevention cost, and probability.

The basic equation for the total annual bulk plant operating costs may be written as follows:

$$C_T = ACOST + OAPC + CAPC + OBC + CBC, \qquad (3.4)$$

where ACOST is the total accident cost, OAPC is the total operating accident prevention cost, CAPC is the total capital accident prevention cost, OBC is the total basic operating cost, and CBC is the total basic capital cost.

In all cases, accident cost increases linearly with increasing probability of the occurrence of the accident.

Both the basic operating cost and the basic capital cost will remain fixed for purposes of analysis. It might be argued that improving the capital accident prevention cost component of an item of hardware, that is also integral in the operation of the plant, could increase efficiency and thereby reduce basic operating costs. For examples, improved interpersonnel communication could both reduce accident probabilities and improve the level of operation. This is not included here.

In order to establish relationships between capital and operating accident prevention costs and the probabilties of design error, operator error, and equipment failure events, the following general observations should be noted:

(a) Case I - Increasing design costs will:
   (i) Reduce design error, and hence design related accident cost.
   (ii) Reduce operator error.
   (iii) Increase capital costs.

(b) Case II - Purchase higher quality basic equipment which will:

  (i) Reduce frequency of equipment failures.

  (ii) Reduce maintenance costs.

  (iii) Increase capital costs.

(c) Case III - Introducting complex equipment will:

  (i) Increase capital costs.

  (ii) Increase maintenance costs.

(d) Case IV - Improved training programs:

  (i) Reduce operator error.

The total cost to operating a bulk plant is now defined as a function of accident probabilities for various undesirable basic events occurring within the plant. There are N such basic events that might occur in the plant, each having a probability p of occurrence. A combination of undesirable events may lead to an accident. To each accident mode a cost is associated. Furthermore, the probability of an undesirable event is linked to the capital cost of preventing the event as well as the operating cost of preventing the event. Depending on the type of event the functions linking the probabilities and the costs may assume one of the following forms:

(a) Group 1:

$$C_0 = 0.0 \tag{3.5a}$$

$$C_c = -K_2 \ln P \tag{3.5b}$$

(b) Group 2:

$$C_0 = K_1 P^{3/2} \tag{3.6a}$$

$$C_c = -K_2 \ln P \tag{3.6b}$$

(c) Group 3:

$$C_0 = -K_1 \ln P \quad (3.7a)$$

$$C_c = -K_1 \ln P. \quad (3.7b)$$

(d) Group 4:

$$C_0 = -K_1 \ln P \quad (3.8a)$$

$$C_c = 0 . \quad (3.8b)$$

These are illustrated in Figures 3.6, 3.7, 3.8, and 3.9 respectively.

The total cost is therefore composed of an accident cost, an accident prevention cost, an accident prevention operating cost as well as a fixed operating and capital costs.

For a given bulk plant it is assumed that the fixed costs remain constant and one may therefore write the total cost T as a function of the probabilities $p_1, \ldots p_N$ only i.e.

$$T = f(p_1, p_2, \ldots, p_N). \quad (3.9)$$

This is a nonlinear equation in N variables. Clearly, $0 \leq p_i \leq$ for all i and $0 \leq T$ for all allowable values of P_i, $i=1,2,\ldots,N$.

It is then desirable to find $p_1^*, p_2^*, \ldots p_N^*$ such that:

$$f(p_1^*, p_2^*, \ldots p_N^*) \leq f(p_1, p_2, \ldots p_N) \quad (3.10)$$

for all allowable choices of p_i, $i = 1,2,\ldots,N$, or in other words, p_i^*, $i = 1,2,\ldots,N$, gives the minimum total cost of operating the bulk plant as a function of the probabilities of undesirable events.

A large number of methods exists for finding such minima, the most popular being methods based on Newton's method in N dimensions. This method, in its basic form, originally used by Ostrowski [119], convergence proven by Kahtorovich [78], presupposes that the Frechet derivative of the nonlinear operator exists (see also Ortega and

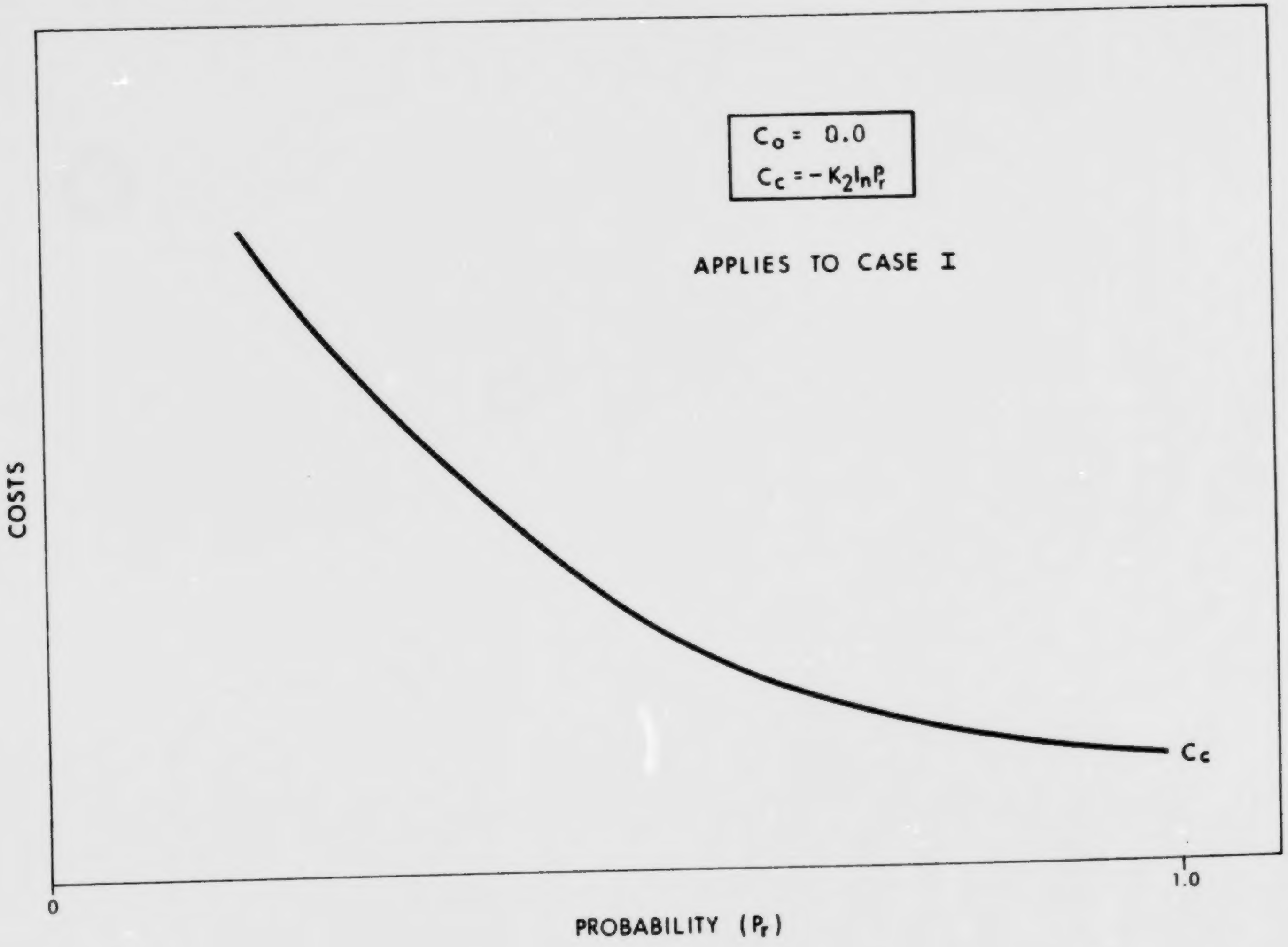


FIGURE 3.6 GROUP 1 COST-PROBABILITY RELATIONSHIP

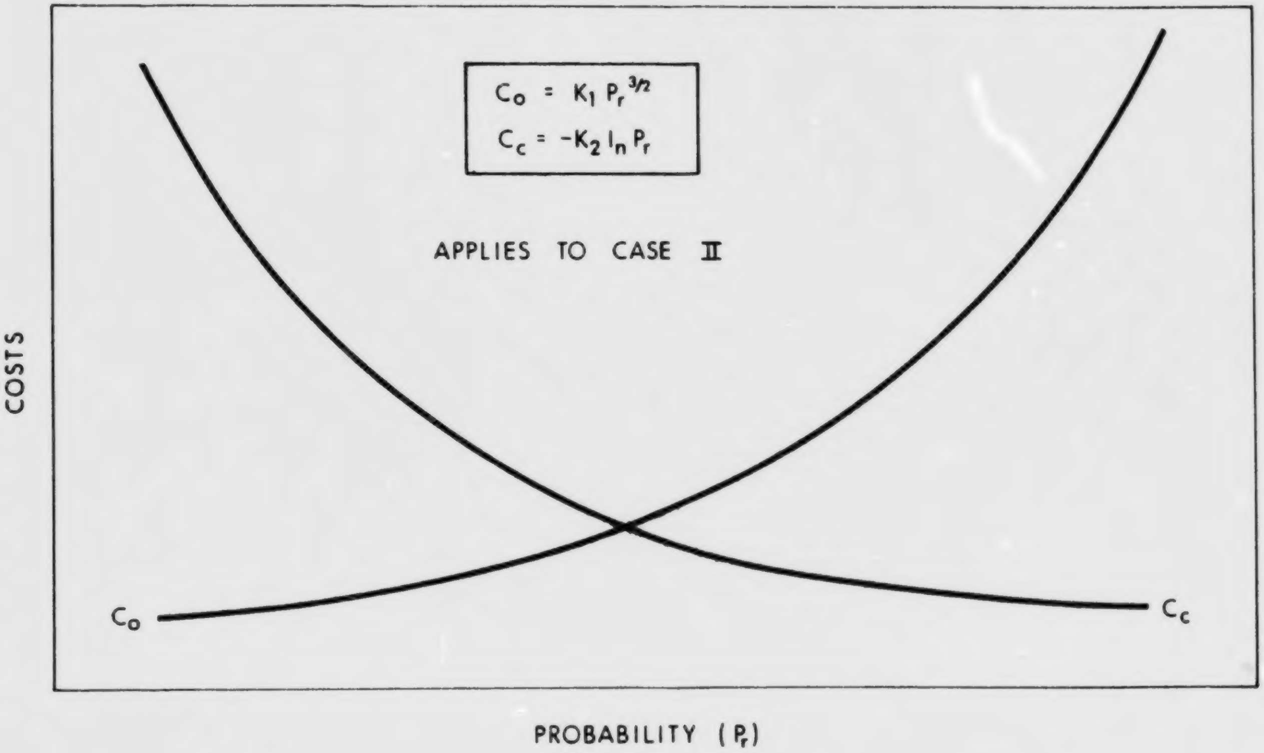


FIGURE 3.7 GROUP 2 COST-PROBABILITY RELATIONSHIPS

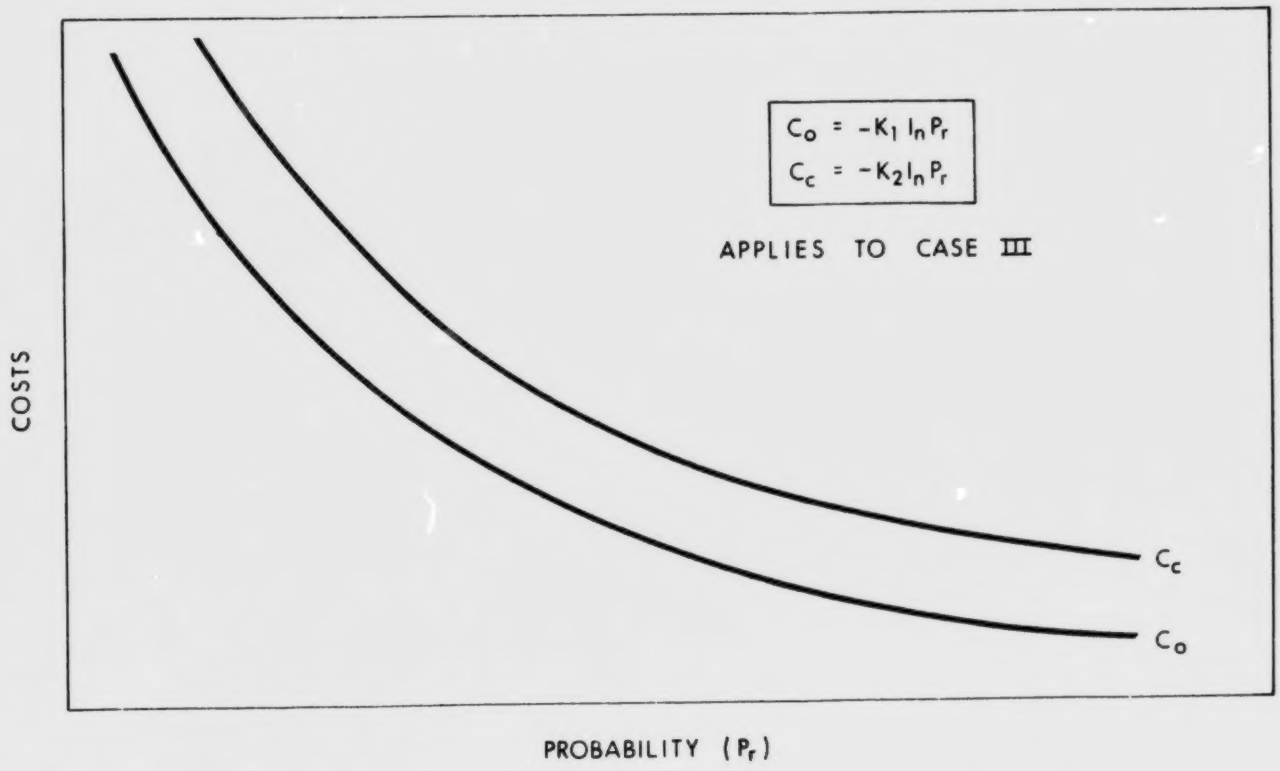


FIGURE 3.8 GROUP 3 COST-PROBABILITY RELATIONSHIP

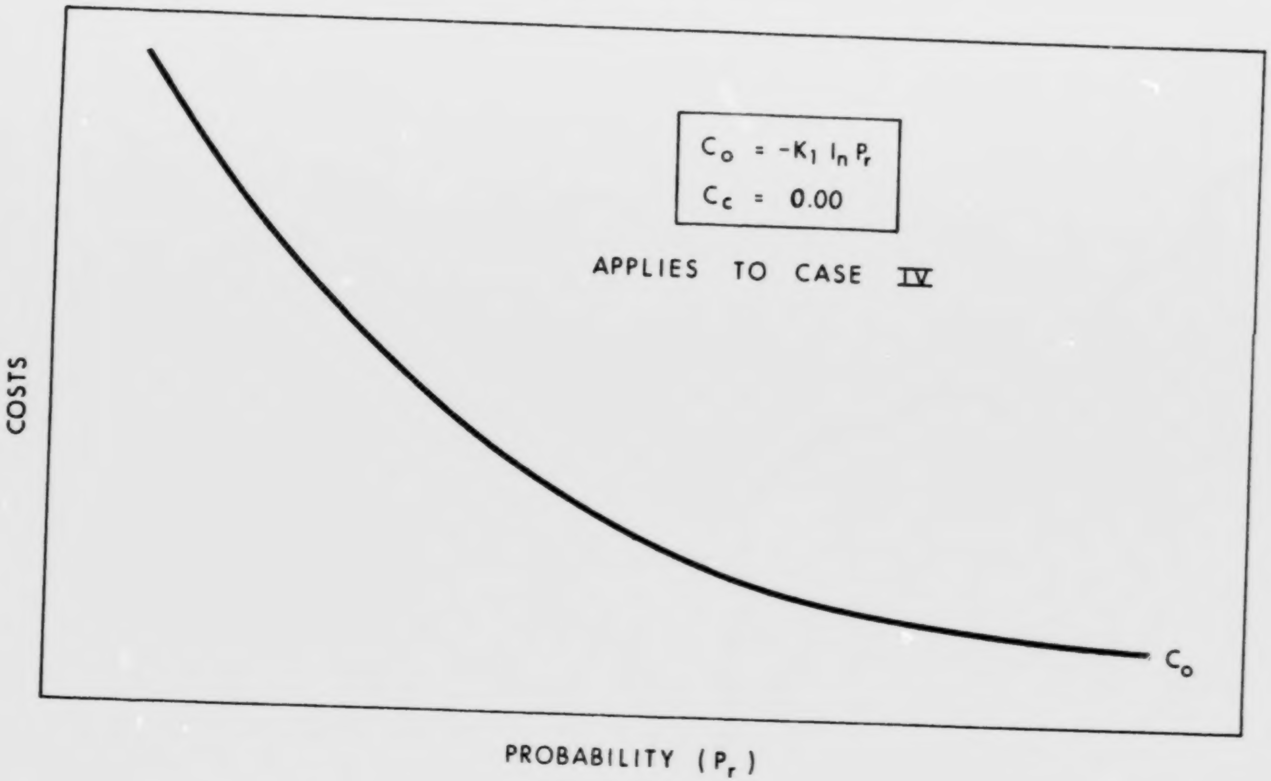


FIGURE 3.9 GROUP 4 COST-PROBABILITY RELATIONSHIPS

Rheinhold [118]). Whereas it is clear that the Frechet derivative exists in our case since the individual equations are fairly simple, it is also clear that the complexity of the total system prevents us from developing the Frechet derivative of the total system. The generalized secant method by Bittner [17] would have been another choice not needing the Frechet derivative. This method suffers from the defect that it requires N initial vectors before the method even can being to compute new interates. It is also very slow.

The methods due to Davidson, Fletcher and Power (see [118]) are also applicable, but avoided because of the nature of our particular problem where we have a large number of equations of a rather simple type.

All of the above methods would be very costly to program and run on our problem.

The method used is a very simple example of the class of descent methods ([118], p. 243). Each variable p_i is increased and decreased by a certain amount in order to find a point on the T hypersurface with a lower cost. This particular method is called the descent method with a cyclical selection of coordinate vectors for descent directions ([118], p.244).

In terms of actual computations the method is described as follows:

For j = 1,2,...,k do the following: With current values of the probabilities set to $p_1, \ldots p_N$, compute for each i = 1,2,...,N:

$$T_0 = f(p_1,\ldots,p_N) \qquad (3.11a)$$

$$T_1 = f(p_1,\ldots,p_{i+\varepsilon},\ldots,p_N) \qquad (3.11b)$$

$$T_2 = f(p_1,\ldots,p_{i-\varepsilon},\ldots,p_N) \qquad (3.11c)$$

$$\text{if } T_1 < T_0 \text{ then } p_i(\text{new}) = p_{i+\varepsilon} ,$$

$$\text{if } T_2 < T_0 \text{ then } p_i(\text{new}) = p_{i-\varepsilon} ,$$

otherwise $p_i(\text{new}) = p_i$.

In this manner we follow the downward trend for each variable in turn.

The functions given in Groups 1, 2 and 3 above are all simple functions with a unique minimum for f restricted to a function of p_i for a fixed i in the range (0,1). It is assumed that minimizing for p_i, $i - 1,2,\ldots,n$, in this range will give a unique minimum; however, this cannot be rigorously proven. Due to the high computation cost of minimizing over all N p_i only subsets of the p_i were chosen. In all tests the procedure found a minimum after a reasonable number of steps.

CHAPTER 4

SOFTWARE PACKAGE AND INPUT VARIABLES

4.1 General Description of Package

The software package developed for this study consists of specific programs written in the Fortran IV language and executed on a CDC 6400 time-sharing general-purpose computer system.

The scope of the study necessitated the development of two programs; namely, one to permit sensitivity computations for individual basic events, and the other to generate results using optimization techniques for any number of basic events.

Combining both these objectives into one package had been contemplated. However, due to both size and complexity the effect would have been unwieldy.

Although, the programs were developed through the analysis of an existing operation, flexibility in their applicability to any other related operation regardless of size, location, throughput, type, age, etc. was a principal objective. Furthermore, accessibility to the average use and simplicity in data manipulation were also primary objectives of program development.

The programs in their completed form allow the user to employ either one of two methods for implementation; namely, the rigorous method or the automatic method.

(a) Rigorous Method

For a particular operation under study, the rigorous method involves evaluating basic event probabilities and costs into the program. This method should provide the user with accurate results for the specific facility under study. The method, however, is tedious and requires suitable analytical background for evaluation of failure event probabilities and appropriate economic data for estimating costs. Details of inputs for the rigorous method are given in Section 4.4.

(b) Automatic Method

The automatic method is an approximate method less rigorous than the previous method, developed to allow the user to utilize the program for a particular operation simply by modifying a few characteristic parameters that automatically reevaluate the base case probabilities and costs. Different levels of refinement are available to the user, depending on the quality of input data and output accuracy requirements. Such levels are described in Section 4.3.

4.2 Program Structure

The programs were written as special purpose programs in Fortran IV for a CYBER 172 computer.

The input data to the programs consists of the probabilities of the basic events, costs for these events as well as pertinent informaation for a specific bulk plant. This specific information consists of the following:

- (a) Number of operations per year.
- (b) Number of tanks filled per operation.
- (c) Factors relating to environment, location, amount of vapour, degree of automation.
- (d) Yearly throughput.
- (e) Volume spilled/accident type.
- (f) Associated costs/accident type.

Based on this information the cost of operating the bulk plant is evaluated using the fault trees and cost trees given in Chapter 3. This cost is then used for particular purposes in each of the following programs.

4.2.1 Sensitivity Program

This program evaluates the cost of operating a bulk plant as a function of a single basic event. All other events are kept constant. The program operates as the basic program module described above with the additional information of the basic event to be considered as well as the range over which sensitivity is desired.

Due to the large variation in size of basic events the range is calculated as

```
DO  4700      IST=2,ISTEP
PP = PQ* (1/2.+FLOAT(ISTEP-IST)/ISTEP)
```

effectively scaling the range to the size of PQ to the original probability value. In addition, the costs for PP = 1.0 and PP = 0 are calculated giving costs for no accident and guaranteed accident for the particular bulk plant.

The flowchart for this program is given in Figure 4.1.

4.2.2. Optimization Program

This program evaluates the optimal operating conditions for a bulk plant relative to a set of basic events. This means that the total cost of the bulk plant is considered to be a function of a small subset of the basic events and optimum is found relative to that subset. The program uses the basic cost evaluator as well as additional data for the subset of basic events to be optimized.

As discussed in Chapter 3 the method used for the optimization is the descent method with a cyclical selection of coordinate vectors for descent direction.

The flowchart for the program is given in Figure 4.2. The flowchart gives the basic outline of the program. The following remarks pertain to the flowchart.

By cyclical selection of the indices is meant that if the indices are $i_1, i_2, i_3, \ldots, i_k$ then the selection is done $i_1, i_2, \ldots, i_k, i_1, i_2, \ldots, i_k, \ldots, i_1, i_2, \ldots, i_k$. The iteration limit is the number of cycles to be performed and the accuracy test is done on the basis of comparing new cost with old cost. If the change in cost is less than a prescribed limit the accuracy requirement is satisfied and an optimal solution is found.

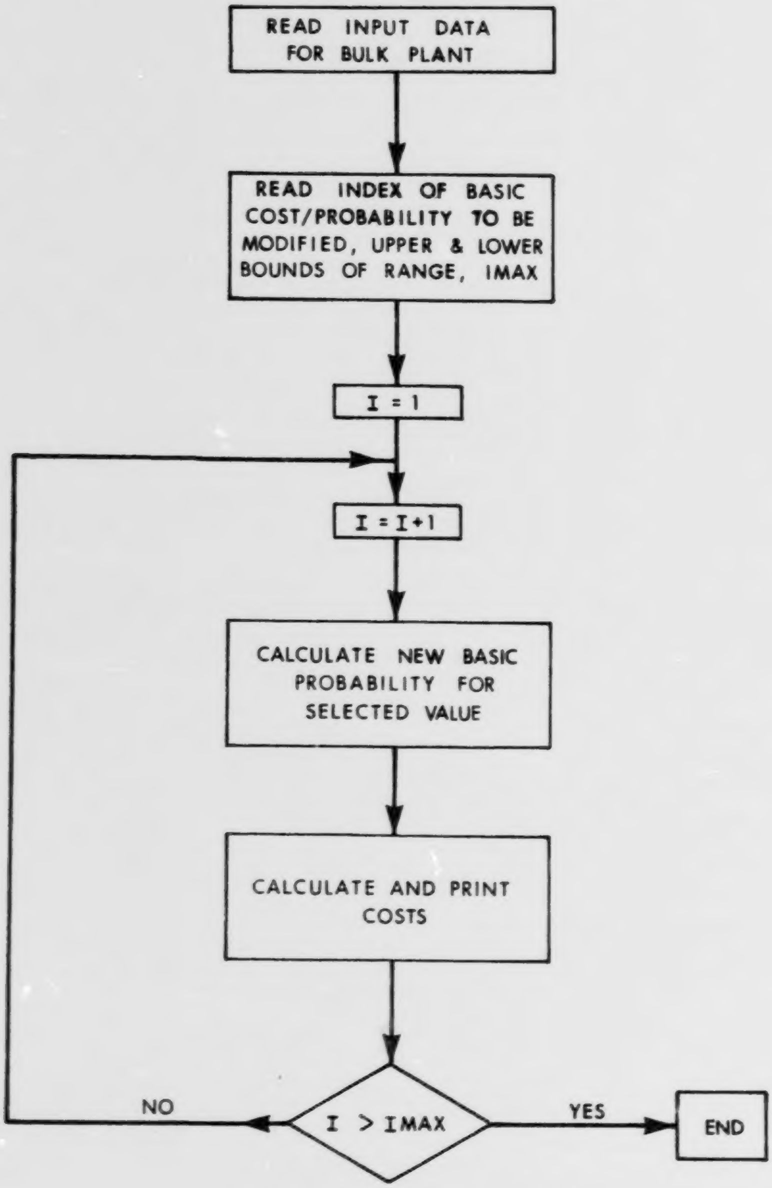

READ INPUT DATA FOR BULK PLANT
READ INDEX OF BASIC COST/PROBABILITY TO BE MODIFIED, UPPER & LOWER BOUNDS OF RANGE, IMAX
I = 1
I = I+1
CALCULATE NEW BASIC PROBABILITY FOR SELECTED VALUE
CALCULATE AND PRINT COSTS
I > IMAX
NO
YES
END

FIGURE 4.1 FLOWCHART FOR SENSITIVITY PROGRAM FOR BULK PLANT

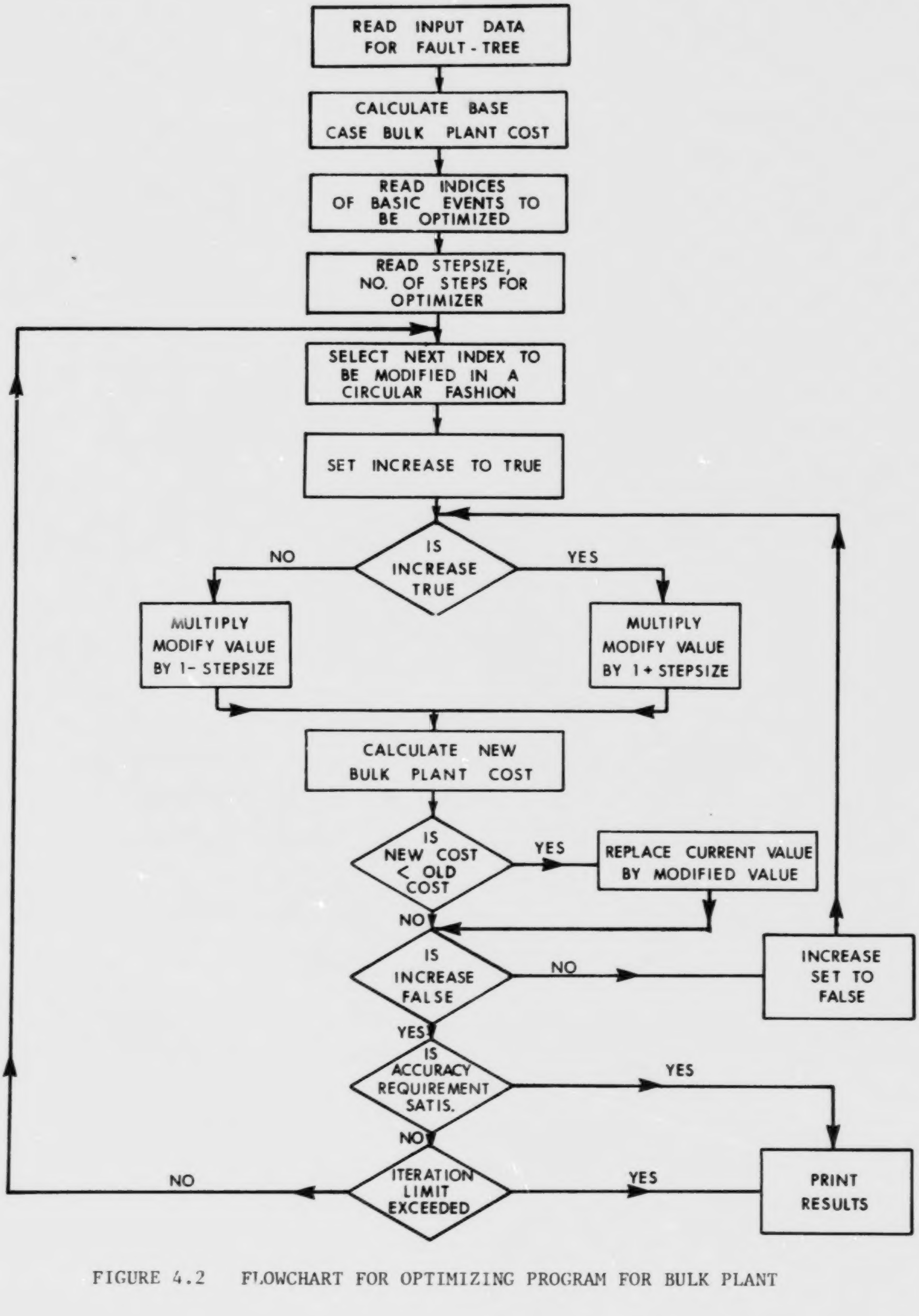

READ INPUT DATA FOR FAULT - TREE
CALCULATE BASE CASE BULK PLANT COST
READ INDICES OF BASIC EVENTS TO BE OPTIMIZED
READ STEPSIZE, NO. OF STEPS FOR OPTIMIZER
SELECT NEXT INDEX TO BE MODIFIED IN A CIRCULAR FASHION
SET INCREASE TO TRUE
IS INCREASE TRUE
NO
YES
MULTIPLY MODIFY VALUE BY 1- STEPSIZE
MULTIPLY MODIFY VALUE BY 1+ STEPSIZE
CALCULATE NEW BULK PLANT COST
IS NEW COST < OLD COST
YES
REPLACE CURRENT VALUE BY MODIFIED VALUE
NO
IS INCREASE FALSE
NO
INCREASE SET TO FALSE
YES
IS ACCURACY REQUIREMENT SATIS.
YES
NO
ITERATION LIMIT EXCEEDED
NO
YES
PRINT RESULTS

FIGURE 4.2 FLOWCHART FOR OPTIMIZING PROGRAM FOR BULK PLANT

4.3 Automatic Method Inputs

The program for the automatic method accepts a number of parameters that characterize an operation. Parameters may be modified or kept at the base case values depending on the level of precision desired by the user. The parameters are grouped according to the level of importance as given below.

4.3.1 Level 1 Essential Parameters

Level 1 input parameters are compulsory inputs. These must be carefully evaluated for the operation in question, and must be implemented into the program regardless of the method of analysis employed. They are tabulated in Table 4.1.

Evaluating the three parameters given in the table and implementing the values into the program will provide a coarse but fair approximation of its operational environment. Propitious methods for evaluating these parameters follow:

(a) Throughput

Averaging incoming annual receipts for the preceding five year period will provide a good evaluation of yearly throughput. The units must be in bbl/year. Receipts that enumerate quantities in metric tons or gallons must have the appropriate conversion factors applied. Although the following conversion is only approximate, the exact value depending upon oil type, it will provide a reasonable estimate:

1 metric ton   709 bbl.

1 bbl = 35 Imperial gallons.

TABLE 4.1

LEVEL 1 INPUT PARAMETERS

Parameter	Abbrev.	Units
Throughput	THRPUT	Avg. No. of Bbl/Year
Number of Operations	NOP	Avg. Yearly No. of Operations
Number of Tanks Filled Per Operation	NTFO	Avg. No. of Tanks Filled/Operation

(b) Number of Operations

First determine the available storage at the end of the fiscal year for each of the last five years, subtracting outgoing receipts from incoming receipts. Averaging this will provide an approximate value for available storage. Alternatively, the available storage of any facility is always on record, however, it must be recognized that all tanks are not in continuous operation, with some undergoing repair, some service or modification. Tanks may also not always be filled to capacity, especially if the terminal handles several different petroleum products that require separate vessels.

The most suitable, yet the most time consuming procedure would be to take 15-20 random stock checks during a representative year and average the result. Once the average amount of product stored at any one time has been evaluated, the average number of transfer operations performed annually can be estimated by dividing the annual throughput by the average amount of product stored at any one time.

It could be argued that the transfer operations, particularly in inland facilities, are continuous. However, for the program to make appropriate evaluations and comparisons an estimate of a fixed number of operations undertaken annually in a bulk terminal is necessary.

(c) Number of tanks filled per operation

The number of tanks filled per operation (NTFO) was computed as follows. It is assumed that all the vessels on the property are filled in each operation. By multiplying this number by an efficiency factor (typically .9) as well as a utilization factor (typically .92) the value of NTFP is arrived at.

4.3.2 Level 2 - Intermediate Parameters

These input parameters are more difficult to evaluate. They should still be computed for the model in order to obtain adequate results. Table 4.2 is a tabulation of these factors.

(a) Volume spilled per incident

From local accident statistics and from the literature and other sources the average numbers of barrels spilt for each of the seven accident types examined should be estimated. Local files would provide the best information for modelling a facility since they would pertain directly. If these evaluations are difficult to develop then the ones given in this study would be suitable. These numbers can be adjusted for any given operation if the analysts feel that certain values are either over or under emphasized for a specific operation.

Table 4.3 lists the average volume spilled for each of the seven major accident types developed for the base case.

TABLE 4.2

LEVEL 2 INPUT PARAMETERS

Parameter	Abbrev.	Units
Volume Spilled Per Incident (7 Acc. Types)	VSPI	Bbl.
Cost Factors (7 Acc. Types)	COSTF	$/Bbl.

TABLE 4.3

AVERAGE SPILL VOLUMES PER SPILL INCIDENT FOR THE SEVEN MAJOR ACCIDENT TYPES

Accident Type	Avg. Vol. Spilled Per Incident (Bbl)
1. Tank Overflow	70
2. Tank Leak	100
3. Tank Rupture	15,000
4. Ancillary Equipment Spill	100
5. Ancillary Equipment Leak	235
6. Fire/Explosion	*1.0
7. Other	75

* Fires do not normally cause spills, rather spills cause fires that are assumed to consume most of the products.

(b) Cost factors

The cost factors represent average dollar per barrel clean-up costs. They are influenced by a number of mitigating factors, (listed in Section 3.4.2.) and are generally a function of terminal throughput. Smaller terminals are normally located inland and larger ones are often associated with a marine environment with higher clean-up costs. Table 4.4 tabulates the cost factors associated with the small, medium-large, and ultra large terminal facilities included in this study, for each of the seven major accident types examined.

Having established the throughput of the facility under study, suitable cost factors can be extrapolated from Table 4.4 and implemented into the program if local records do not exist or are difficult to obtain. Table 4.4 can also be employed in conjunction with local records to help establish the base scenario.

4.3.3 Level 3 - Refined Parameters

The level 3 input parameters have been developed into the program to provide refinements to the basic inputs, based upon operational characteristics of lesser importance, relative to the level 1 input parameters. Table 4.5 lists these secondary parameters indicating their area of applicability.

TABLE 4.4

COST FACTORS FOR THE SEVEN MAJOR ACCIDENT TYPES
FOR TERMINALS WITH DIFFERENT ANNUAL THROUGHPUTS

Accident Type	COSTF $/Bbl Spilled		
	Small (10,000,000 bbl)	Medium-Large (150,000,000 bbl)	Ultra Large (Conceptual) (300,000,000 bbl)
Tank Overflow	32	53	106
Tank Leak	47	78	150
Tank Rupture	22	35	70
Ancil. Equip. Spill	32	53	106
Ancil. Equip. Leak	31	52	104
Fire/ Explosion	50,000	84,000	150,000
Other	30	50	100

TABLE 4.5

LEVEL 3 - REFINEMENT PARAMETERS

Parameter	Abbreviation	Applicability
Location Factor	LOCF	Sabotage events
Experience Factor	EXPFACT, E.F.	Operator errors
Age Factor	AGEFACT, A.F.	Design errors Equipment failures
Consequence Factor Modifier	CONFACT	To modify consequence factors, tailoring them to a particular study
Experience Factor	OEXPF	Modifies the operating accident prevention cost associated with human error (e.g. more experienced person commands higher per bbl costs to employ)
Quality Factor	QFACT	Modifies the capital accident prevention costs associated with equipment failure (e.g. better quality equipment commands higher per bbl costs to employ)
Environmental Factor	ENVF	Natural phenomenon related events
Automation Factor	AUTOF	Fail safe system errors

All the factors in Table 4.5 have been set to 1.0 for the base operation since the effects of these parameters are already reflected in the statistical inputs. A factor of 1.0 therefore represents the characteristics of base operation and the users need only to modulate this factor either upward or downward, depending on the characteristics of their own operation.

It must be stressed that the factors are used simply to modify the base event evaluations of the base case chosen in this study in order to create a base case representative of any other installation to which the model is applied.

4.4 General Description of Input Variables

The probabilistic and cost variables were evaluated through the application of specialist knowledge to empirical risk data. These data were collected mainly from applicable statistical sources, previous reports, field investigations, and expert opinions. There are different classes of input value requiring several alternative approaches to their determination.

(a) One-Way Unconditional Enumerative Input

The one-way unconditional enumerative inputs include those that are derived implicitly from established statistics, and that can have a direct influence on the operation modelled, but that in turn cannot be affected by the latter. For example, environmental parameters such as frost, rain, electrical storms for any study region selected are well documented and their probability for occurrence easily evaluated from the enumerative data collected. Events of this nature are binary (either they occur or they do not occur) and their statistics are accurately recorded.

(b) Two-Way Conditional Enumerative Inputs

Two-way conditional enumerative inputs apply to those events for which populations of measurements have been collected, but which do not apply to any one operation specifically. Gathering a maximum amount of information will normally yield better results than attempting to isolate a specific operation as a population base. If a certain accident event has never occurred at the installation under study, it does not imply that the probability of such an event happening is reduced to zero.

In applying comprehensive statistics to a particular operation one must nevertheless necessarily incorporate a conditional element into the analysis. It is this "conditional" element that causes the selected input to develop a two-way characteristic. If, for example, under controlled testing conditions, a certain unit of equipment develops a unique rate of failure based on statistical averaging, and is subsequently assigned an individual failure probability within a given latitude of confidence, then operating that device in the field under better or more adverse circumstances should modify that failure probability accordingly. A similar argument can be applied to costs. Unit costs can per se differ significantly even on a local level from published rates, depending on numerous conditional averages. A certain amount of inference making is therefore required even when evaluating probabilities and costs for two-way conditioal enumerative inputs.

(c) Inference Inputs

Inference inputs are those for which a sound data base has not been established. This could be a result either of the nature of the information desired or its availability. This type of input is often associated with the human element, which normally has an intrastructure that is too complex to readily quantify. Certain general guidelines on human error rate values for different situations have, however, been established [13], and these used as a basis for the evaluation herein.

4.5 Base Case and Rigorous Method Input Variables

The base event and associated cost input variables corresponding to the Fault-Cost tree and its subtrees, as described generally in Figures 3.1 to 3.2, are summarized in Table 4.6. The resulting values represent the following:

(a) Trees

The probabilities and accident prevention costs of the seven major categories of accident incorporated into the analysis are evolved by means of logic networks composed of basic events linked into a hierarchy of resultant events that ultimately culminate in each major accident type.

Although each tree is composed of a unique set of events, its structure can recur in any other network. This is used to facilitate the programming. In Table 4.6, within the column labelled "TREE", digits without an alphabetical suffix represent a group of trees with the same structures treated equivalently within the program. Each accident type consists of three such trees. The trees are labelled consecutively from 1 through 21 for purposes of identification. Trees with digits followed by the letter "A" represent a group that differs from the first type by requiring different treatment within the program. Trees of this type only occur in the networks of the first three major accident events in the program even though they are listed in Table 4.6 after all the trees of the first type.

The third type of tree occurs only in the "fire/explosion" network and is represented at the end of Table 4.6 by a digit followed by the letter "S".

(b) Events

The column labelled "event" in Table 4.6 numbers the basic events incorporated into each tree. Following each event number three descriptions are given, the first identifying the failure event, the second indicating the human element provided in countering the failure event, and the last listing the respective capital countermeasures.

TABLE 4.6

FAULT-COST TREE INPUTS FOR THE BASE CASE BULK PLANT

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
		TANK OVERFLOW				
		DESIGN				
	1	INCORRECTLY SPEC. TANK CAPAC.	.00001			1
		GOOD TANK IDENTIFICATION			.00085	
	2	POOR CHOICE OF GAUGING SYSTEM	.0004			1
		RELIABLE GAUGING SYSTEM			.001	
	3	INADEQUATE FILLING MARGINS	.00007			1
		ADEQUATE FILLING MARGINS			.00045	
	4	OTHER	.00015			1
		UPGRADE OTHER			.00045	
	5	INAD. COMMUNICATION SYSTEM	.0006			1
		RELIABLE COMMUNICATION SYSTEM			.00055	
	6	DESIGN CODES NOT MET	.00007			1
		ENSURE DESIGN CODES MET			.00085	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
		OPERATOR ERROR				
2	1	CHARGE WRONG TANK	.004			4
		TRAINING PROGRAM		.00085		
	2	TANKS NOT GAUGED	.003			4
		INSURE TANKS PROPERLY GAUGED		.0015		
	3	LEVEL CONTROL READING ERROR	.004			4
		TRAINING PROGRAM		.001		
	4	UNDERESTIMATE FILLING TIME	.006			4
		TRAINING PROGRAM		.0015		
	5	COMMUNICATION ERROR	.003			4
		TRAINING PROGRAM		.00085		
	6	OVERESTIMATE AVAILABLE CAP.	.004			4
		TRAINING PROGRAM		.0015		

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	7	OTHER	.001			4
		IMPROVE OTHER		.0004		
					.00006	
		EQUIPMENT				
3	1	VALVE FAILURE	.0007			2
		MAINTAIN VALVES		.0005		
		RELIABLE VALVES			.0015	
	2	COMPUTER CONTROL MALFUNCTION	.0005			2
		MAIN COMPUTER SYSTEM		.00065		
		GOOD COMPUTER SYSTEM			.005	
	3	COMMUNICATIONS FAILURE	.0007			2
		MAINTAIN. COMMUN. LINKS		.00035		
		GOOD COMMUNICATION LINKS			.0015	
	4	GAUGE FAILURE	.0025			2
		MAINTAIN GAUGES		.0015		
		RELIABLE GAUGES			.0016	
	5	OTHER FAILURE	.0005			2
		MAINTAIN OTHER		.00015		
		OTHER			.00085	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
		TANK LEAK				
		DESIGN				
4	1	INAD. TANK WALL THICKNESS	.0003			1
		RELIABLE THICKNESS DESIGN			.0005	
	2	FOUNDATION DESIGN ERROR	.0015			1
		PROPER FOUNDATION DESIGN			.002	
	3	POOR CHOKE FOR TANK MATERIAL	.00045			1
		PROPER MATERIAL SELECTION			.0005	
	4	TANK SUPPORT DESIGN ERROR	.00045			1
		RELIABLE DESIGN OF SUPPORTS			.0005	
	5	DESIGN CODES NOT MET	.0002			1
		ENSURE DESIGN CODES MET			.0005	
	6	OTHER	.00025			1
		OTHER			.00025	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	7	INADEQUATE LINING	.002			1
		ADEQUATE LINING SELECTED			.0005	
		TANK LEAK				
		OPERATOR ERROR				
5	1	FAIL. TO NOTE LEVEL DISCREP.	.007			4
		TRAINING PROGRAM		.002		
	2	LACK OF SUPERVISION	.002			4
		TRAINING PROGRAM		.00025		
	3	RECORDS NOT MAINTAINED	.004			4
		TRAINING PROGRAM		.00025		
	4	IGNORANCE	.003			4
		PENALIZE TRAINING PROGRAM		.0002		
	5	DERELICTION OF DUTY	.002			4
		PENALIZE		.00025		

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	6	PROPER CORROSION STEPS NOT TAKEN	.0015			4
		TRAINING PROGRAM		.0008		
					.000065	
	7	CARELESSNESS	.006			4
		TRAINING PROGRAM		.001		
	8	DISREGARD SAFETY REGULATIONS	.005			4
		PENALIZE		.00025		
	9	OTHER	.0006			4
		OTHER		.00025		
		TANK LEAK				
		EQUIPMENT				
6	1	FAILURE BY CORROSION	.0035			2
		REGULAR INSPECTION		.0015		
		CORROSION INHIBITORS			.0085	
	2	TANK FATIGUE	.0003			2
		REGULAR TANK INSPECTION		.0011		
		GOOD TANK MATERIAL			.01	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	3	VALVE FAILURE	.0006			2
		MAINTAIN VALVES		.00085		
		RELIABLE VALUES			.0035	
	4	LINING FAILURE	.002			2
		REGULAR LINING INSPECTION		.002		
		GOOD QUALITY LINING			.0085	
	5	OTHER	.00015			2
		OTHER		.0003		
		OTHER			.0035	
		TANK RUPTURE				
		DESIGN ERROR				
7	1	UNCONVENTIONAL TANK TYPE	.00011			1
		PROPER TANK SELECTION			.00065	
	2	INADEQUATE FOUNDATION DESIGN	.0003			1
		GOOD FOUNDATION DESIGN			.0025	
	3	FATIGUE FAILURE	.0003			1
		ADEQUATE STRESS CONSIDERATION			.00085	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	4	UNSUITABLE TANK MATER. CHOSEN	.000055			1
		APPROPRIATE TANK MATER.CHOSEN			.00065	
	5	INADEQUATE CONSIDERATION OF TEMP. INDUCED STRESS	.00022			1
		ADEQUATE STRESS CONSIDERATION			.00085	
	6	DESIGN CODES NOT MET	.000055			1
		ENSURE CODES ARE MET			.00065	
	7	OTHER				1
		OTHER				
		TANK RUPTURE				
		OPERATOR				
8	1	INCORRECT FILLING PROCEDURE	.0013			4
		TRAINING PROGRAM		.0017		
	2	DISREGARD SAFETY REGULATIONS	.004			4
		PENALTIES		.00085		

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	3	CARELESSNESS	.005			4
		PENALTIES		.001		
					.00025	
	4	LACK OF SUPERVISION	.0015			4
		IMPROVE SUPERVISION		.00085		
					.00015	
	5	OTHER	.0015			4
		OTHER		.00045		
					.0001	
		TANK RUPTURE				
		EQUIPMENT				
9	1	TANK CORROSION	.002			2
		CORROSION PREVENTION MEASURES		.002		
		CORROSION INHIBITORS			.015	
	2	INADEQUATE LINING	.0015			2
		MAINTAIN TANK LINING		.0017		
		PROPER LINING			.0065	
	3	OTHER	.0002			2
		OTHER		.0005		
		OTHER			.0035	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	4	TANK WALL FAILS	.0002			2
		MAINTAIN & INSPECT TANK WALLS		.001		
		GOOD TANK MATERIAL			.01	
		ANCILLARY EQUIPMENT SPILL				
		DESIGN				
10	1	POOR LAYOUT	.006			3
		GOOD LAYOUT DESIGN			.02	
	2	INADEQUATE METERING	.005			3
		ADEQUATE METERING SYSTEM			.009	
	3	INADEQUATE VALVE SYSTEM	.003			3
		RELIABLE VALVE ARRANGEMENT			.015	
	4	INADEQUATE PROTECTION FROM VEHICULAR COLLISION	.0095			3
		BARRIERS			.009	
	5	POOR CONNECTION DESIGN	.0015			3
		GOOD CONNECTION DESIGN			.003	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	6	INADEQUATE FAIL SAFE SYSTEM	.0025			3
		RELIABLE WARNING SYSTEM			.003	
	7	OTHER	.0015			3
		OTHER			.003	
		ANCILLARY EQUIPMENT SPILL				
		OPERATOR				
11	1	CLOSE WRONG VALVE	.065			1
		TRAINING PROGRAM		.035		
	2	COMMUNICATION ERROR	.085			1
		IMPROVE COMMUNICATION		.014		
	3	INCORRECT PRESSURE READING	.02			1
		TRAINING PROGRAM		.03		
	4	DISREGARD DANGER SIGNALS	.065			1
		PENALIZE		.007		

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	5	MONITORING ERROR	.045			1
		TRAINING PROGRAM		.02		
	6	CARELESSNESS	.15			1
		PENALTIES		.03		
	7	OTHER	.004			1
		OTHER		.007		
		ANCILLARY EQUIPMENT SPILL				
		EQUIPMENT				
12	1	PIPE RUPTURE	.01			2
		MAINTAIN PIPES		.017		
		GOOD PIPE MATERIAL			.04	
	2	PIPE CORROSION	.02			2
		CORROSION PREV. MEASURES		.02		
		CORROSION INHIBITORS			.07	
	3	OTHER	.009			2
		OTHER		.002		
		OTHER			.007	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	4	CONNECTION FAILURE	.009			2
		MAINTAIN CONNECTIONS		.006		
		GOOD CONNECTIONS			.015	
	5	IMPACT FAILURE	.002			2
		MAINTAIN SIGNS & REGULATIONS		.002		
		ENSURE BARRIERS ADEQUATE			.015	
	6	VALVE FAILURE	.01			2
		MAINTAIN VALVES		.01		
		RELIABLE VALVES			.03	
	7	VALVE CORROSION	.02			2
		CORROSION PREV. MEASURES		.015		
		CORROSION INHIBITORS			.05	
	8	GASKET FAILURE	.01			2
		MAINTAIN GASKETS		.01		
		RELIABLE GASKETS			.03	
	9	COMMUNICATIONS FAILURE	.002			2
		MAINTAIN COMMUNICATIONS EQUIP.		.011		
		GOOD COMMUNICATIONS EQUIP.			.035	
	10	PUMP FAILURE	.006			2
		MAINTAIN PUMPS		.017		
		RELIABLE PUMPS			.05	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
		ANCILLARY EQUIPMENT LEAK				
		DESIGN				
13	1	LAYOUT ERROR	.005			3
		GOOD LAYOUT			.015	
	2	INADEQUATE METERING SYSTEM	.01			3
		RELIABLE METERING SYSTEM			.007	
	3	IMPROPER PIPE SIZING	.0055			3
		PROPER PIPE SIZING			.01	
	4	INADEQUATE VALVE SYSTEM	.0055			3
		RELIABLE VALVE SYSTEM			.01	
	5	POOR SEAL DESIGN	.0055			3
		GOOD SEAL CONSIDERATIONS			.007	
	6	INAD. DRAINAGE CONSIDERATIONS	.003			3
		GOOD DRAININGS			.01	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	7	OTHER	.003			3
				0		
		OTHER			.004	
	8	INAD. LEAK DETECTION SYSTEM	.015			3
		DETECTION SYSTEM			.007	
		ANCILLARY EQUIPMENT LEAK				
		OPERATOR				
14	1	DERELICTION OF DUTY	.03			1
		PENALIZE		.006		
	2	OVERSIGHT	.05			1
		TRAINING PROGRAM		.018		
	3	CARELESSNESS	.10			1
		PENALIZE		.012		
	4	NOT NOTICED	.12			1
		TRAINING PROGRAM		.018		

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	5	NOT REPORTED	.025			1
		REPROVE		.006		
		ANCILLARY EQUIPMENT LEAK				
		EQUIPMENT				
15	1	METER FAILURE	.0025			2
		MAINTAIN METERS		.025		
		RELIABLE METERS			.035	
	2	PIPE FAILURE BY CORROSION	.045			2
		MAINTAIN PIPES		.04		
		GOOD PIPE MATERIAL			.08	
	3	SEAL LEAK	.02			2
		MAINTAIN SEALS		.015		
		ADEQUATE SEALS			.04	
	4	COUPLING LEAK	.009			2
		MAINTAIN CONNECTIONS		.015		
		GOOD COUPLINGS			.015	
	5	OVERPRESSURE	.006			2
		ESTABLISH REGULATIONS		.008		
		ESTABLISH PRESSURE REQUIRE.			.008	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	6	VALVE FAILURE	.015			2
		MAINTAIN VALVES		.025		
		RELIABLE VALVES			.04	
	7	PUMP LEAK	.025			2
		MAINTAIN PUMPS		.025		
		GOOD PUMPS			.04	
	8	OTHER	.025			2
		OTHER		.008		
		OTHER			.015	
		FIRE OR EXPLOSION				
		DESIGN				
16	1	POOR TANK LAYOUT	.0015			3
		GOOD TANK LAYOUT			.04	
	2	INAD. FIRE FIGHTING EQUIP.	.009			3
		SELECT PROPER FIRE FIGHTING EQUIPMENT			.015	
	3	INADEQUATE WATER SUPPLY	.0035			3
		ENSURE WATER AVAILABILITY			.026	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	4	NO SAFETY REGULATIONS	.0035			3
		PREPARE GOOD SAFETY REGS.			.0045	
	5	POOR PLANT LAYOUT	.0015			3
		GOOD PLANT LAYOUT			.03	
	6	INADEQUATE GROUNDING	.0015			3
		PROPER GROUNDING			.006	
	7	INADEQUATE INERTING SYSTEM	.0035			3
		GOOD INERTING SYSTEM			.006	
	8	COVERAGE INADEQUATE	.01			3
		ADEQUATE COVERAGE			.025	
		FIRE OR EXPLOSION				
		OPERATOR				
17	1	IGNORE REGULATIONS	.025			1
		PENALIZE		.01		

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	2	NOT ALERT	.015			1
		TRAINING PROGRAM		.04		
	3	COMMUNICATION FAILURE	.035			1
		IMPROVE COMMUNICATIONS		.03		
	4	POOR GROUNDING	.007			1
		PENALIZE		.02		
	5	CARELESSNESS	.015			1
		PENALIZE		.03		
	6	IGNORANCE	.015			1
		TRAINING PROGRAM		.065		
	7	OTHER	.007			1
		OTHER		.01		

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
		FIRE OR EXPLOSION				
		EQUIPMENT				
18	1	ALARM FAILS	.0015			2
		MAINTAIN ALARM		.015		
		GOOD ALARM			.13	
	2	COMMUNICATION FAILURE	.004			2
		MAINTAIN COMMUNICATION SYSTEM		.009		
		PROPER COMMUNICATION SYSTEM			.085	
	3	INADEQUATE FIRE FIGHTING EQPT	.08			2
		MAINTAIN FIRE FIGHTING EQUIP.		.06		
		DEPENDABLE FIRE FIGHTING EQPT			.6	
	4	OTHER	.004			2
		OTHER		.0045		
		OTHER			.04	
		OTHER				
		NATURAL PHENOMENON				
19	1	EARTHQUAKE				3
		EARTHQUAKE MONITORING				
		EARTHQUAKE MONITORING				

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	2	SEVERE STORM	.087			3
		WARNING SYSTEM		.015		
		WEATHER MONITORING			.02	
	3	TSUNAMI				3
		WARNING SYSTEM				
		WAVE MONITORING				
	4	OTHER	.004			3
		OTHER		.004		
		OTHER			.006	
		OTHER				
		SABOTAGE				
20	1	ARSON	.0065			1
		SECURITY		.02		
		SECURITY SYSTEM			.025	
	2	INSANITY	.0033			1
		SECURITY		.01		
		SECURITY SYSTEM			.025	
	3	REVENGE	.0011			1
		SECURITY		.007		
		SECURITY SYSTEM			.007	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
	4	OTHER	.0011			1
		OTHER		.002		
		OTHER			.007	
		OTHER				
		OTHER				
21	1	OTHER	.022			2
		OTHER		.006		
		OTHER			.0095	
		TANK OVERFLOW				
		DESIGN				
		FAIL SAFE SYSTEM				
1A	1	INAD. AUTO. SHUTDOWN	.006			
		ADEQUATE DESIGN			.019	
	2	INADEQUATE ALARM	.009			
		ADEQUATE SYSTEM DESIGN			.005	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
		OPERATOR				
2A	1	NOT MAINT. AUTO. SHUTDOWN	.035			4
		TRAINING PROGRAM		.009		
	2	NOT MAINT. ALARM	.02			4
		TRAINING PROGRAM		.007		
	3					
		EQUIPMENT				
3A	1	AUTOMATIC SHUTDOWN FAILS	.025			3
		MAINTAIN AUTOMATIC SHUTDOWN		.05		
		GOOD EQUIPMENT			.1	
	2	ALARM FAILS	.01			3
		MAINTAIN ALARM		.015		
		GOOD EQUIPMENT			.044	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
		TANK LEAK				
4A	1	NO SHELL THICKNESS TESTING	.05			2
		IMPROVE S.T. TESTING		.009		
		GOOD TESTING EQUIPMENT			.0055	
5A	1	INADEQUATE HYDROSTATIC TEST.	.075			2
		ENSURE HYDROSTATIC TESTING		.03		
		GOOD TESTING EQUIPMENT			.022	
6A	1	NO TANK SUPPORT TESTING	.1			2
		REGULARLY ASSESS SUPPORTS		.025		
		GOOD TESTING PROGRAM			.017	
7A	1	OTHER	.025			2
		OTHER		.018		
		OTHER			.011	
		TANK RUPTURE & BOILOVER				
		RELIEF DEVICE FAILURE				

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
		DESIGN				
8A	1	NO VACUUM	.05			1
		ADEQUATE VACUUM SYSTEM			.008	
	2	INAD. PRESSURE RELIEF SYSTEM	.02			1
		GOOD PRESSURE RELIEF SYSTEM			.01	
	3					
		OPERATOR				
9A	1	INAD. MAINT. OF VACUUM	.06			4
		TRAINING PROGRAM				
	2	INAD. MAINT. OF PRESS. RELIEF	.08			4
		TRAINING PROGRAM				
					.005	

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
		EQUIPMENT				
10A	1	VACUUM FAILS	.03			3
		MAINTAIN VACUUM		.005		
		DEPENDABLE VACUUM			.05	
	2	RELIEF VALVE FAILS	.08			3
		MAINT. PRESS RELIEF SYSTEM		.003		
		DEPEND. RELIEF VALVES			.07	
		FIRE OR EXPLOSION				
		IGNITION				

TABLE 4.6 (continued)

Tree	Event	Description	Prob. of Failure (P_r)	Oper. Acc. Prev. Cost (O_c)	Capital Acc. Prev. Cost (C_c)	Class of Event
11	1	ARSON	.0065			
	2	LIGHTNING	.017			
	3	CARELESSNESS	.013			
	4	ELECTROSTATIC CHARGE	.039			
	5	ACT OF GOD	.024			
	6	ELECTRICAL	.026			
	7	OTHER	.0065			

The tree and event number refer to the location of the only failure event within the network, with the corresponding accident prevention events listed for completion. The accident prevention events, although occurring in networks similar to the failure events, are treated quite differently within the program.

The values of the events are given in Table 4.6 following their description. The probabilities of failure for the first 9 trees are given as failures per tank per operation. Those for trees 10 through 21 represent failure probability per operation. The prevention costs are given in cents/bbl through per tank corresponding to the failure events in trees 1 through 9, and as cent/bbl through for the others.

From the above it is possible to closely evolve an empirical set of subtrees from the general tree of Figure 3.1.

Evaluation of the base event inputs and cost factors was carried out through a combination of the analytical and statistical methods generally used in fault trees [89] and economic optimization work.

The class of event relates to the group number given in Section 3.5 that defines the function to which the event is applied.

The factors in Table 4.6 were arrived at using judgement based on available information. They must be assumed to have fairly large confidence intervals. In particular, factors involving human error and human behavior may vary greatly depending on circumstances and specific individual responses.

CHAPTER 5

RESULTS

5.1 Nature and Structure of Results

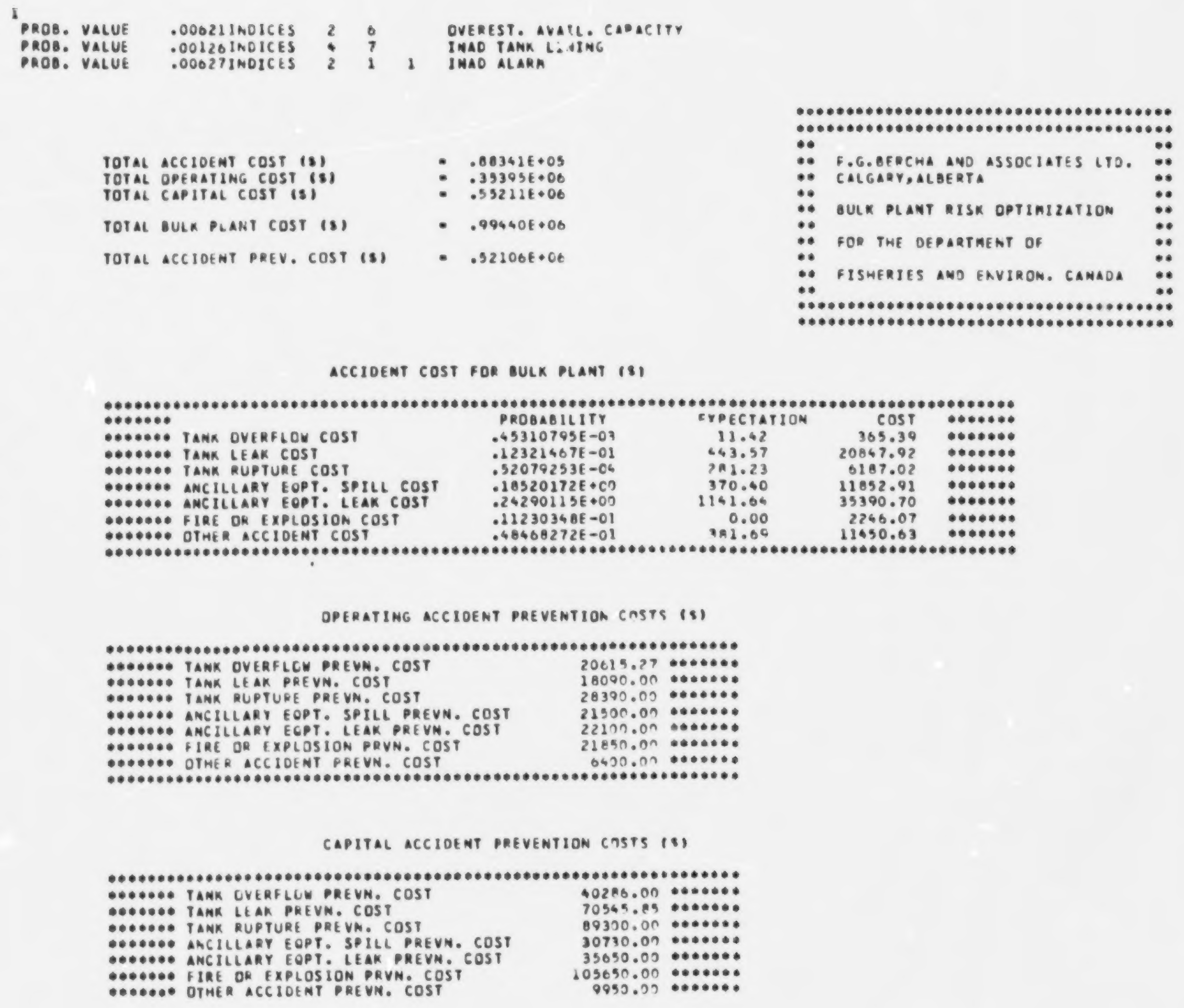
The results were generated utilizing the software package developed on the basis of the analysis presented in Chapter 3 as well as the input parameters described in Chapter 4.

Two principal categories of results were generated; single and multiple input optimization results. The single event input optimizations are cost sensitivity studies whereas the multiple input investigations were optimizations of a set of factors.

Figures 5.1 and 5.2 show the form of the printout generated by the software package, for each of the two types of optimizations. Detailed listings of the software packages are found in Appendix A.

The balance of this chapter presents a series of numerical studies carried out for specified bulk plants, with variation of selected variables directed at risk optimization. A subsequent section is given on the application of the program to different types of bulk plants. Discussion of the significance of the results is included.

The results are all optimization perturbations of the base case bulk plant described generally in Section 5.2, except for those given in Section 5.5 which show risk variation for different types and sizes of plants. No optimization is done for the latter group of plants.



```
1
 PROB. VALUE     .00621INDICES    2    6         OVEREST. AVAIL. CAPACITY
 PROB. VALUE     .00126INDICES    4    7         INAD TANK L.4ING
 PROB. VALUE     .00627INDICES    2    1    1    INAD ALARM

                                                                      ************************************
                                                                      ************************************
                                                                      **                                **
      TOTAL ACCIDENT COST ($)            =  .88341E+05                **  F.G.BERCHA AND ASSOCIATES LTD.  **
      TOTAL OPERATING COST ($)           =  .35395E+06                **  CALGARY,ALBERTA               **
      TOTAL CAPITAL COST ($)             =  .55211E+06                **                                **
                                                                      **  BULK PLANT RISK OPTIMIZATION  **
      TOTAL BULK PLANT COST ($)          =  .99440E+06                **                                **
                                                                      **  FOR THE DEPARTMENT OF         **
      TOTAL ACCIDENT PREV. COST ($)      =  .52106E+06                **                                **
                                                                      **  FISHERIES AND ENVIRON. CANADA **
                                                                      **                                **
                                                                      ************************************
                                                                      ************************************

                          ACCIDENT COST FOR BULK PLANT ($)

      *************************************************************************************************
      *******                                   PROBABILITY         EXPECTATION         COST   *******
      ******* TANK OVERFLOW COST               .45310795E-03           11.42           365.39  *******
      ******* TANK LEAK COST                   .12321467E-01          443.57         20847.92  *******
      ******* TANK RUPTURE COST                .52079253E-04          281.23          6187.02  *******
      ******* ANCILLARY EQPT. SPILL COST       .18520172E+00          370.40         11852.91  *******
      ******* ANCILLARY EQPT. LEAK COST        .24290115E+00         1141.64         35390.70  *******
      ******* FIRE OR EXPLOSION COST           .11230348E-01            0.00          2246.07  *******
      ******* OTHER ACCIDENT COST              .48468272E-01          381.69         11450.63  *******
      *************************************************************************************************


                          OPERATING ACCIDENT PREVENTION COSTS ($)

      ******************************************************************
      ******* TANK OVERFLOW PREVN. COST                20615.27 *******
      ******* TANK LEAK PREVN. COST                    18090.00 *******
      ******* TANK RUPTURE PREVN. COST                 28390.00 *******
      ******* ANCILLARY EQPT. SPILL PREVN. COST        21500.00 *******
      ******* ANCILLARY EQPT. LEAK PREVN. COST         22100.00 *******
      ******* FIRE OR EXPLOSION PRVN. COST             21850.00 *******
      ******* OTHER ACCIDENT PREVN. COST                6400.00 *******
      ******************************************************************


                          CAPITAL ACCIDENT PREVENTION COSTS ($)

      ******************************************************************
      ******* TANK OVERFLOW PREVN. COST                40286.00 *******
      ******* TANK LEAK PREVN. COST                    70545.85 *******
      ******* TANK RUPTURE PREVN. COST                 89300.00 *******
      ******* ANCILLARY EQPT. SPILL PREVN. COST        30730.00 *******
      ******* ANCILLARY EQPT. LEAK PREVN. COST         35650.00 *******
      ******* FIRE OR EXPLOSION PRVN. COST            105650.00 *******
      ******* OTHER ACCIDENT PREVN. COST                9950.00 *******
```

FIGURE 5.1 SAMPLE SENSITIVITY PRINTOUT

```
                                                                           ****************************************
TOTAL ACCIDENT COST ($)          =      97271.                             ****************************************
TOTAL OPERATING COST ($)         =     349798.                             **                                    **
TOTAL CAPITAL COST ($)           =     549042.                             **  F.G.BERCHA AND ASSOCIATES LTD.    **
                                                                           **  CALGARY,ALBERTA                   **
TOTAL BULK PLANT COST ($)        =     996111.                             **                                    **
                                                                           **  BULK PLANT RISK OPTIMIZATION      **
TOTAL ACCIDENT PREV. COST ($)    =     513840.                             **                                    **
                                                                           **  FOR THE DEPARTMENT OF             **
                                                                           **                                    **
                                                                           **  FISHERIES AND ENVIRON. CANADA     **
                                                                           **                                    **
                                                                           ****************************************
                                                                           ****************************************


                          ACCIDENT COST FOR BULK PLANT ($)

*************************************************************************************************
*******                                PROBABILITY        EXPECTATION        COST     *******
******* TANK OVERFLOW COST             .11982252E-01         301.95        9662.49    *******
******* TANK LEAK COST                 .12979356E-01         467.26       21961.07    *******
******* TANK RUPTURE COST              .52079253E-04         281.23        6187.02    *******
******* ANCILLARY EQPT. SPILL COST     .18520172E+00         370.40       11852.91    *******
******* ANCILLARY EQPT. LEAK COST      .23008865E+00        1081.42       33523.92    *******
******* FIRE OR EXPLOSION COST         .13162892E-01           0.00        2632.58    *******
******* OTHER ACCIDENT COST            .48468272E-01         381.69       11450.63    *******
*************************************************************************************************


                          OPERATING ACCIDENT PREVENTION COSTS ($)

*******************************************************************
******* TANK OVERFLOW PREVN. COST                18630.00 *******
******* TANK LEAK PREVN. COST                    18090.00 *******
******* TANK RUPTURE PREVN. COST                 28390.00 *******
******* ANCILLARY EQPT. SPILL PREVN. COST        21500.00 *******
******* ANCILLARY EQPT. LEAK PREVN. COST         19938.41 *******
******* FIRE OR EXPLOSION PRVN. COST             21850.00 *******
******* OTHER ACCIDENT PREVN. COST                6400.00 *******
*******************************************************************


                          CAPITAL ACCIDENT PREVENTION COSTS ($)

*******************************************************************
******* TANK OVERFLOW PREVN. COST                35946.00 *******
******* TANK LEAK PREVN. COST                    70479.00 *******
******* TANK RUPTURE PREVN. COST                 89300.00 *******
******* ANCILLARY EQPT. SPILL PREVN. COST        30730.00 *******
******* ANCILLARY EQPT. LEAK PREVN. COST         36986.98 *******
******* FIRE OR EXPLOSION PRVN. COST            105650.00 *******
******* OTHER ACCIDENT PREVN. COST                9950.00 *******
*******************************************************************

                               THE CURRENT INDEX =     4

PROB. VALUE     .02680    INDEX  15    2    BASIC EVENT          PIPE CORROSION
```

FIGURE 5.2   SAMPLE OPTIMIZATION PRINTOUT

5.2 Base Case Bulk Plant

The model is based on the use of an "average" bulk plant. This average bulk plant is called the base case bulk plant. Using such a base case bulk plant facilitates the implementation of the model and the analysis of the results. Any given bulk plant may be considered a perturbation of the base case with a corresponding parameter variation.

The base case bulk plant was derived from the study of an intermediate sized tank farm associated with an inland Western Canadian product refinery. The principal operating parameters of the plant are summarized in Table 5.1, while Table 5.2 summarizes fundamental economic parameters for the plant and Table 5.3 gives capacities. All input data values previously derived in Chapter 4 relate to the base case.

The selected facility is a relatively modern inland facility capable of handling crude as well as black and white petroleum products. The white oils are transported into the tank farm through a pipeline, for subsequent distribution by tanker truck to the consumer. The principal product handled by the distribution facility is gasoline, stored primarily for distribution to local filling stations. Diesel, stove, heating oils, as well as smaller amounts of other finished products are also handled.

The crude portion of the operation relates to a product refinery associated with the facility. The crude is delivered in parcel amounts by train truck and railway car, and is stored in tanks to provide continuous feedstock for the refinery. Tankage for storing refinery

TABLE 5.1

PRINCIPAL OPERATING PARAMETERS
FOR THE BASE CASE BULK PLANT

Parameter	Value
Operators	7
Maintenance Personnel	3

TABLE 5.2

SUMMARY OF FUNDAMENTAL ECONOMIC PARAMETERS FOR BASE CASE BULK PLANT

Parameters	Values
Total Operating Cost	10¢/bbl throughput
a) Capital Cost	5½¢/bbl throughput
b) Operating, Accident & Other Costs	4½¢/bbl throughput
Salaries	2¢/bbl

TABLE 5.3

SUMMARY OF CAPACITIES

FOR THE BASE CASE BULK PLANT

Parameters	Values
No. of Tanks	18
Total Tankage (Bbl)	750,000
Throughput (M Bbl/yr)	10,000

products is located in the refinery area, and is therefore not included as part of the bulk plant operation. Figure 5.3 is a schematic of the operation used as a base case.

A total of ten employees comprising seven operators and three maintenance personnel are employed in the operation.

5.3 Individual Event Optimization

5.3.1 Scenario No. 1 - Pipe Corrosion

The corrosion of pipelines continues to be one of the principal causes of leakage, resulting in considerable annual expenditures attributable to repair or replacement of liners that become corroded, cleaning up spills, restoring sensitive environmental regions that are impacted, and writing off lost product.

A sensitivity analysis was performed on the pipe corrosion event in a fault tree. The sensitivity analysis essentially involved the incrementation of accident probability concurrently with associated cost increments, permitting observation of the distribution of associated accident and accident prevention costs, and consequent changes in total plant costs. Results of the corrosion analysis are detailed in the balance of this section. Table 5.4 summarizes the direct results of the optimization analysis. The optimum operating probability of the accident event is evidently about one third of the one which appears to exist for the base case given in Table 5.5. Some saving can therefore be obtained in total bulk plant costs by operating at the optimum. Figures 5.4, 5.5, 5.6 and 5.7 graphically depict the relationships among probability of pipe corrosion and total bulk plant cost, total

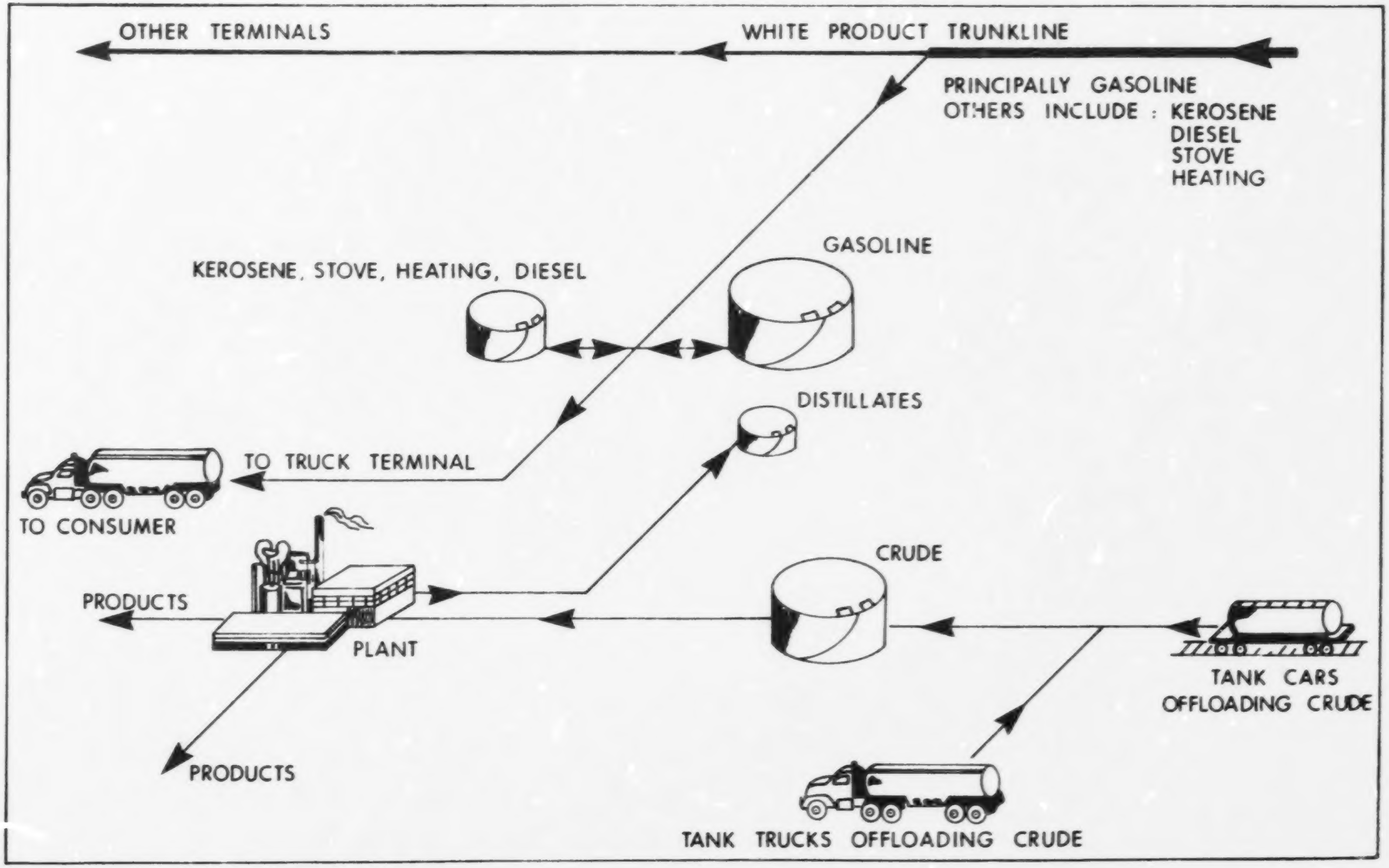


FIGURE 5.3 SCHEMATIC OF BULK PLANT OPERATIONS

TABLE 5.4

BULK PLANT COST SCENARIO

ACHIEVED BY OPTIMIZING PIPE CORROSION

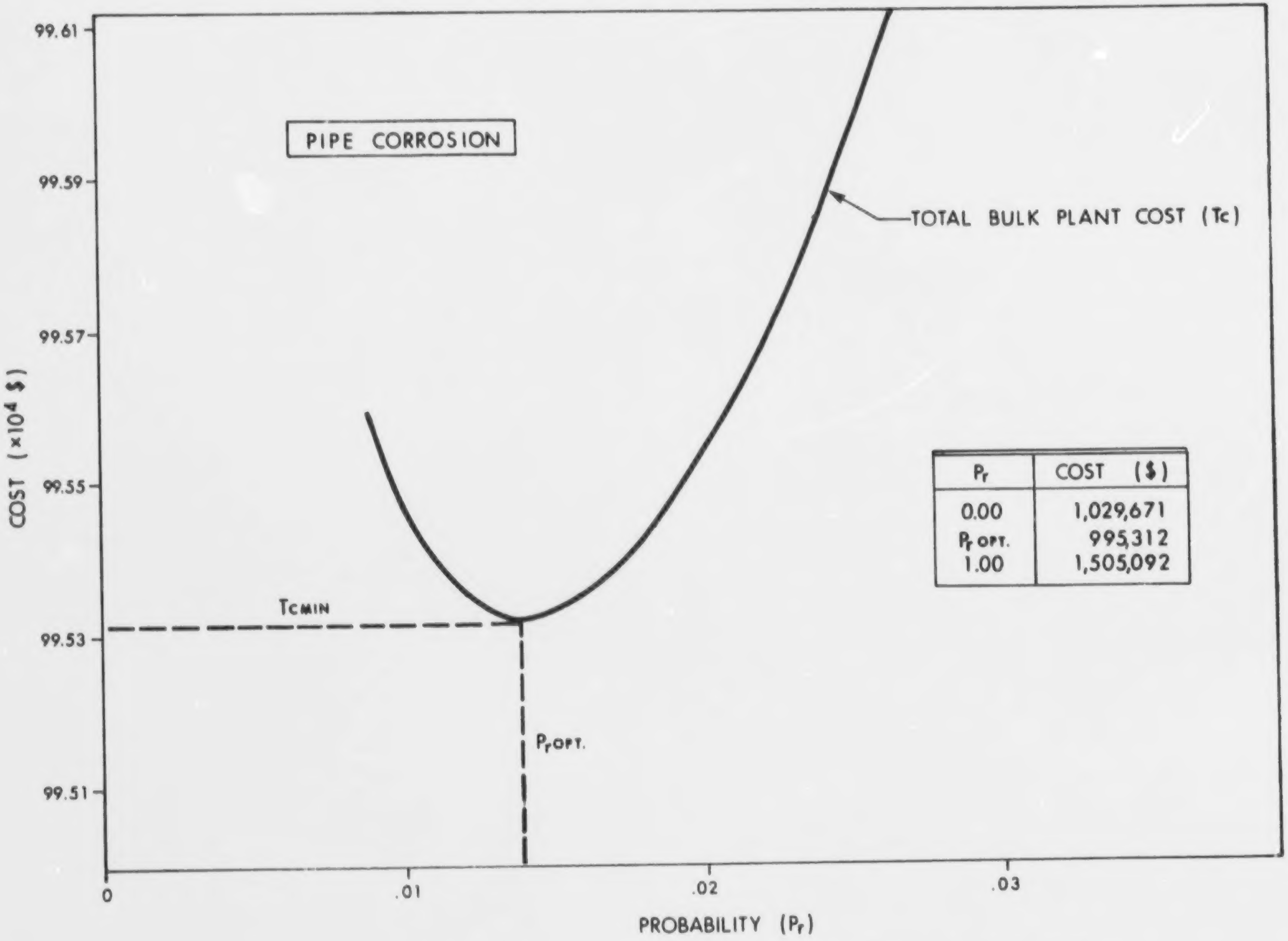
Total Accident Cost	$ 95,940
Total Operating Accident Prevention Cost	$133,654
Total Capital Accident Prevention Cost	$380,717
Total Bulk Plant Cost	$995,312

TABLE 5.5

BASE CASE BULK PLANT

COST SCENARIO

Total Accident Cost	$ 99,162
Total Operating Accident Prevention Cost	$136,960
Total Capital Accident Prevention Cost	$377,705
Total Bulk Plant Cost	$998,830



P_r	COST (\$)
0.00	1,029,671
$P_{r\,OPT.}$	995,312
1.00	1,505,092

FIGURE 5.4 PLOT OF TOTAL BULK PLANT COST VS. PROBABILITY OF PIPE CORROSION

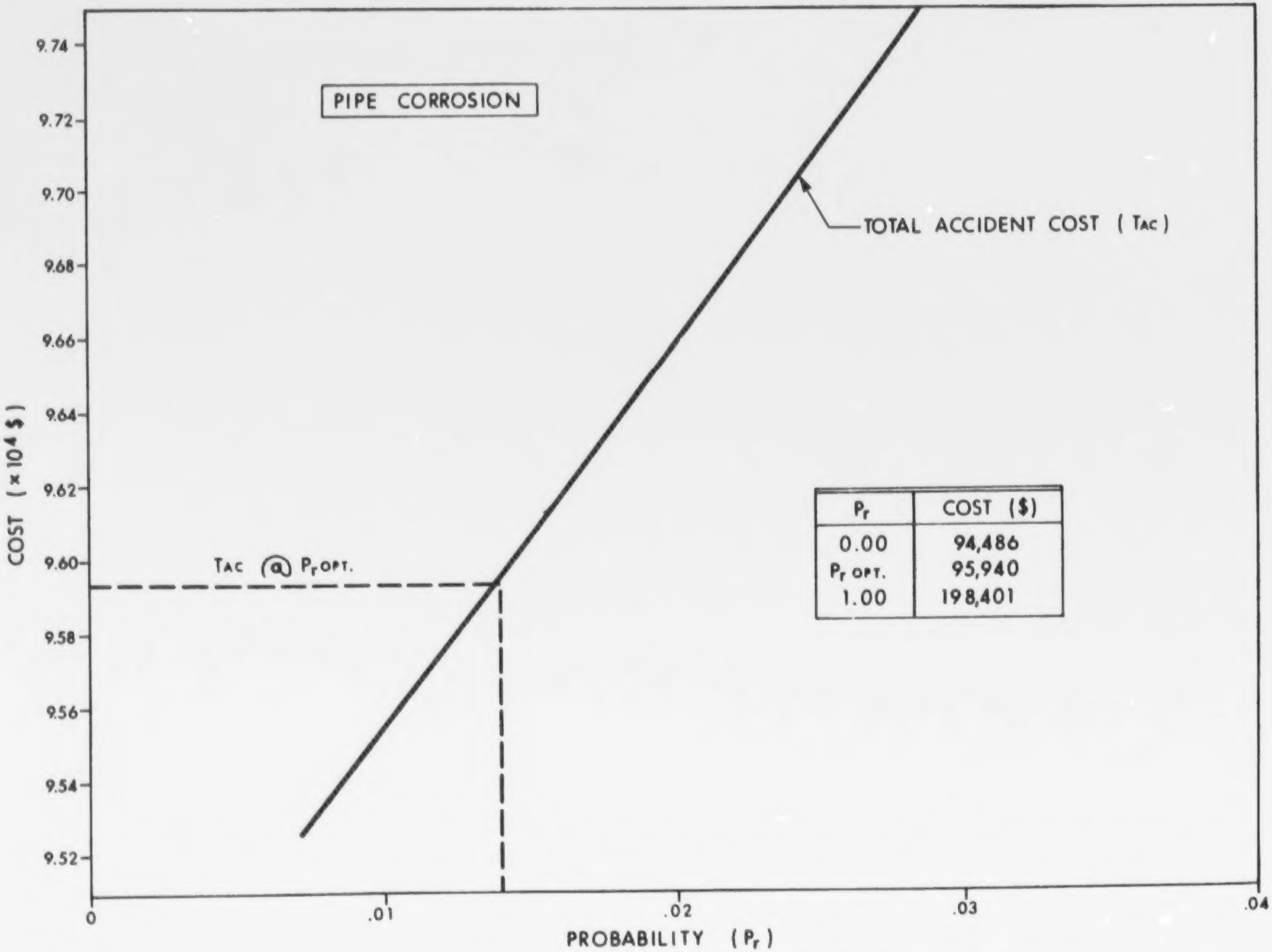


FIGURE 5.5 PLOT OF TOTAL ACCIDENT COST VS. PROBABILITY OF PIPE CORROSION

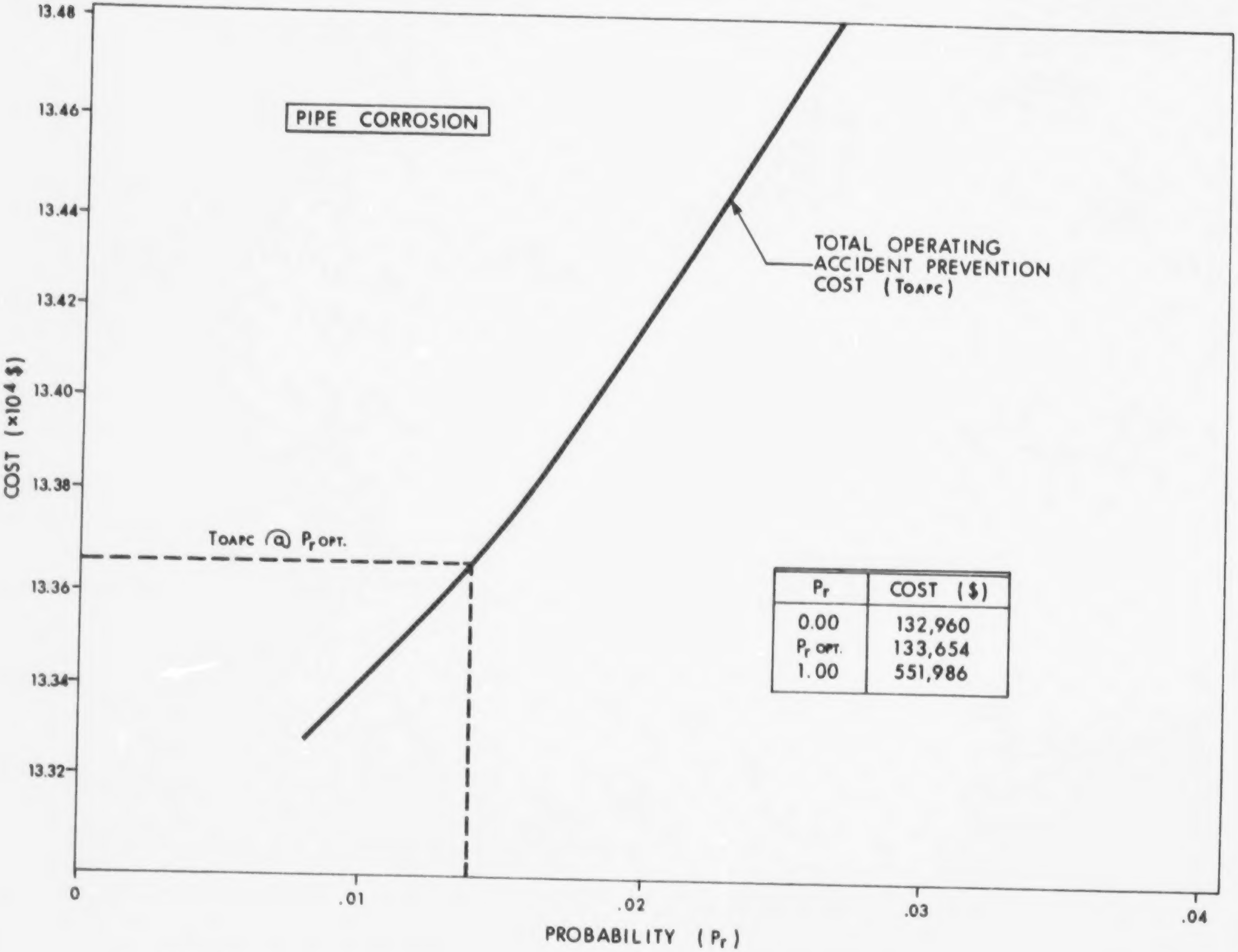
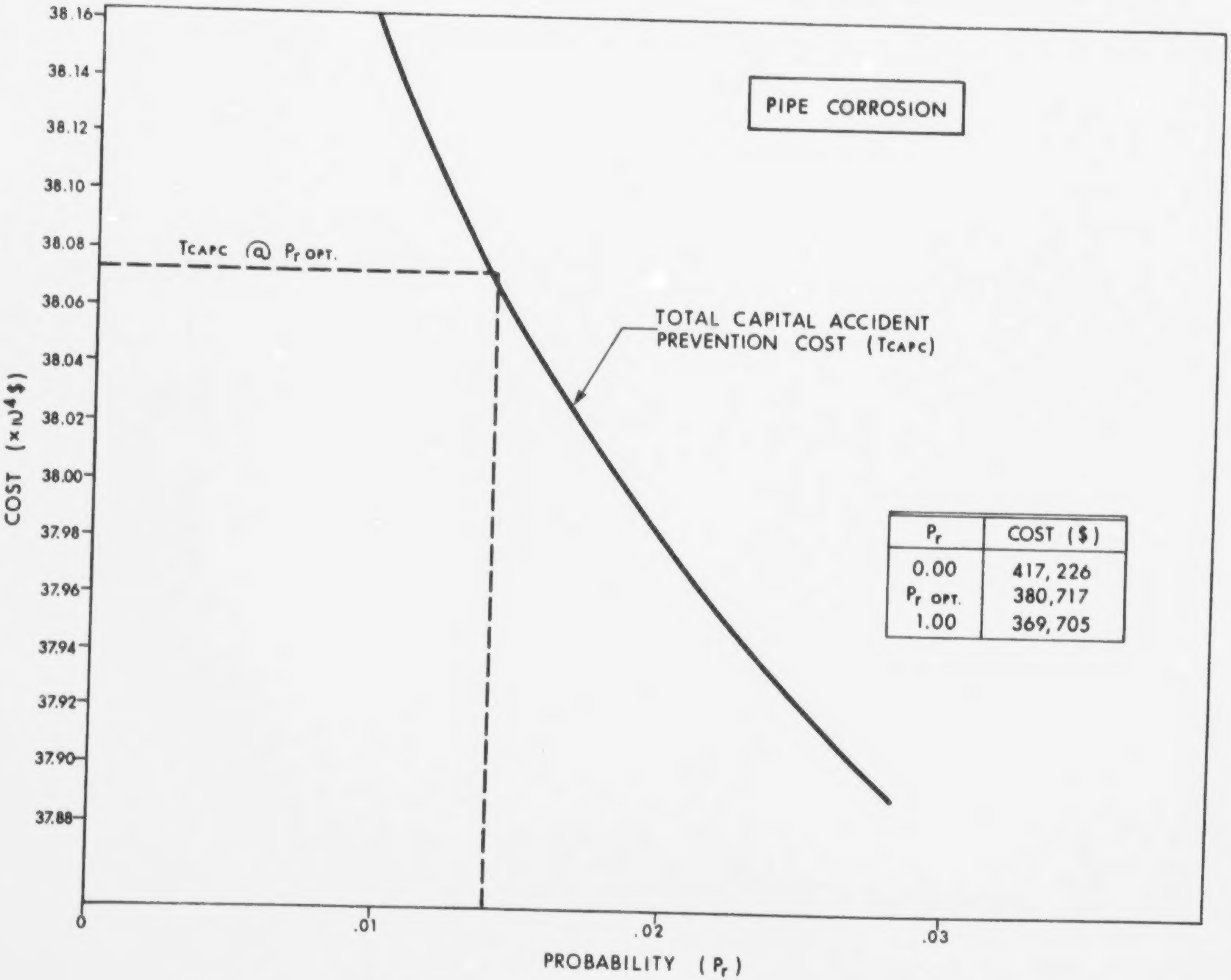


FIGURE 5.6 PLOT OF TOTAL OPERATING ACCIDENT PREVENTION COST VS. PROBABILITY OF PIPE CORROSION



P_r	COST ($)
0.00	417,226
P_r OPT.	380,717
1.00	369,705

FIGURE 5.7 PLOT OF TOTAL CAPITAL ACCIDENT PREVENTION COST VS. PROBABILITY OF PIPE CORROSION

accident cost, total operating and accident prevention cost, and total capital and accident prevention cost. The results clearly show that equal amounts of operating and capital accident prevention costs do not provide the same rate of return in terms of accident prevention for the case under study. For that case, the analytical location of the plant is to the right of the minimum of the total bulk plant cost curve, showing that operations are not at the optimum. The plant must therefore currently be employing an experienced man to inspect for signs of corrosion as part of his regular duties.

The results suggest that substitution of $3,300 of capital accident prevention costs for the same amount in operating accident prevention costs would further reduce accident costs by $3,200. This suggestion can be explained as follows. Better pipe material, inhibitors, paints, and coatings will significantly reduce the occurrence of corrosion. On the other hand, an inspector being paid to check for corrosion that must have already occurred to be noticeable will incur further costs in corrosion repairs. The preventive measure in this case is better than the corrective measure. The addition of better corrosion inhibitors does not, however, supplant the employment of an individual to check for corrosion, since 100% effectiveness of those methods cannot be guaranteed. If the facility resorted to complex corrosion control measures that required sophisticated equipment, the plant operating costs would increase as well, because of the additional costs of hiring specialized servicemen to maintain the system, as well as the added expense of specialized replacement parts.

Operation on either side of the optimum would not be economically justifiable. Accordingly, the optimum level of operation indicated, balanceing accident clean-up and reclamation costs against prevention costs minimized total costs should ideally be attained.

5.3.2 Scenario No. 2 - Seal Leak

Figures 5.8, 5.9, 5.10, and 5.11 describe the sensitivity analysis results associated with the seal leak event.

5.3.3 Scenario No.3 - Inadequate Inspection

Figures 5.12, 5.13, and 5.14 graphically depict the results of the sensitivity studies for inadequate inspection.

5.4 Optimization

In the optimization analysis, a selected number of basic accident events is varied concurrently to permit observation of their cumulative effect on total and other plant costs. If each event was investigated individually it would be difficult to gauge the total effect. The optimization capacity of the model allows any number of events to analyzed concurrently so that their combined effect on minimizing total annual cost, and the net effect on the annual operating and capital accident cost can also be readily obtained from the outputs. In the balance of the section, three different combinations of events were analyzed, with the results detailed primarily in tabular form with some subsidiary discussion.

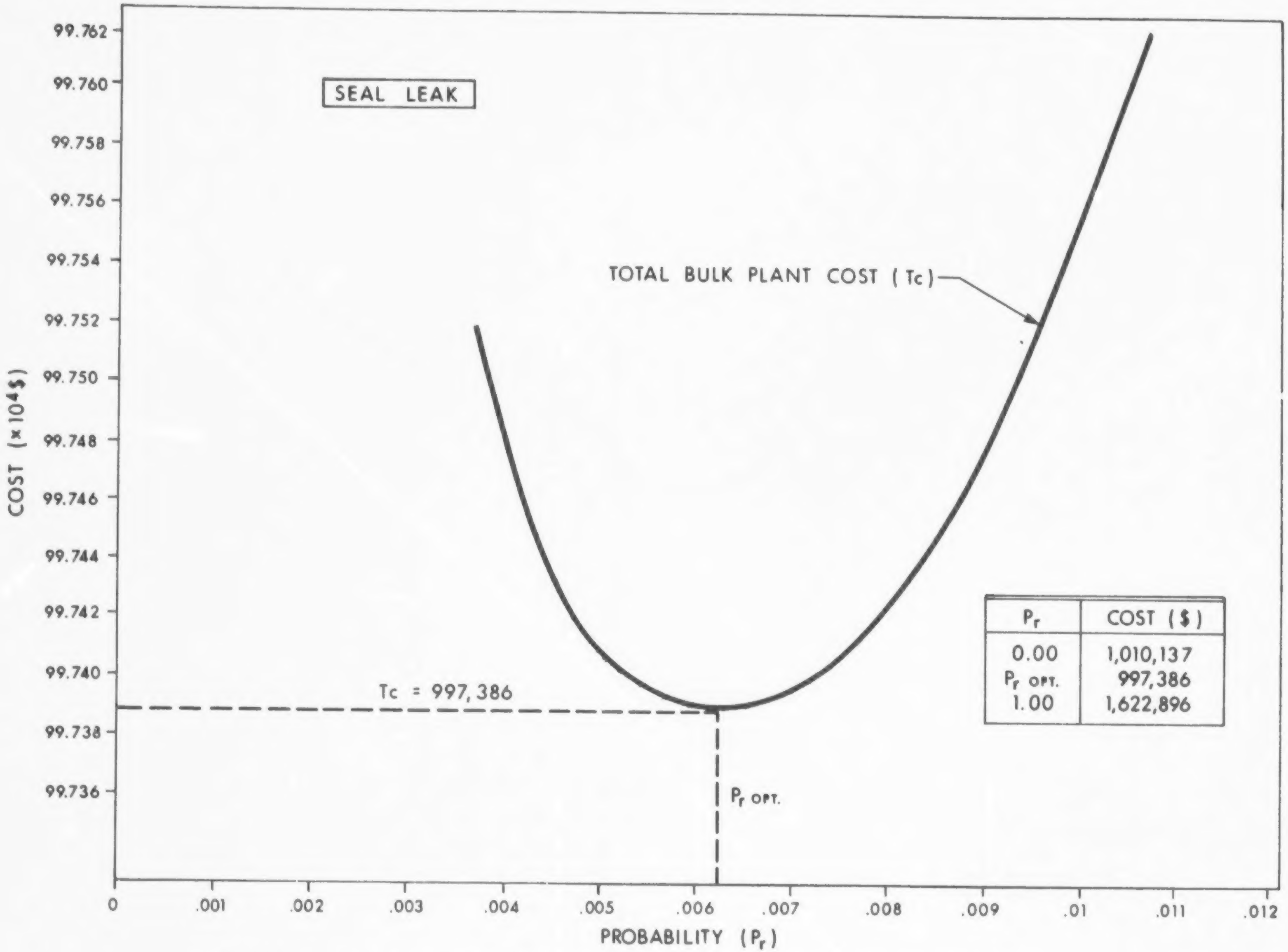
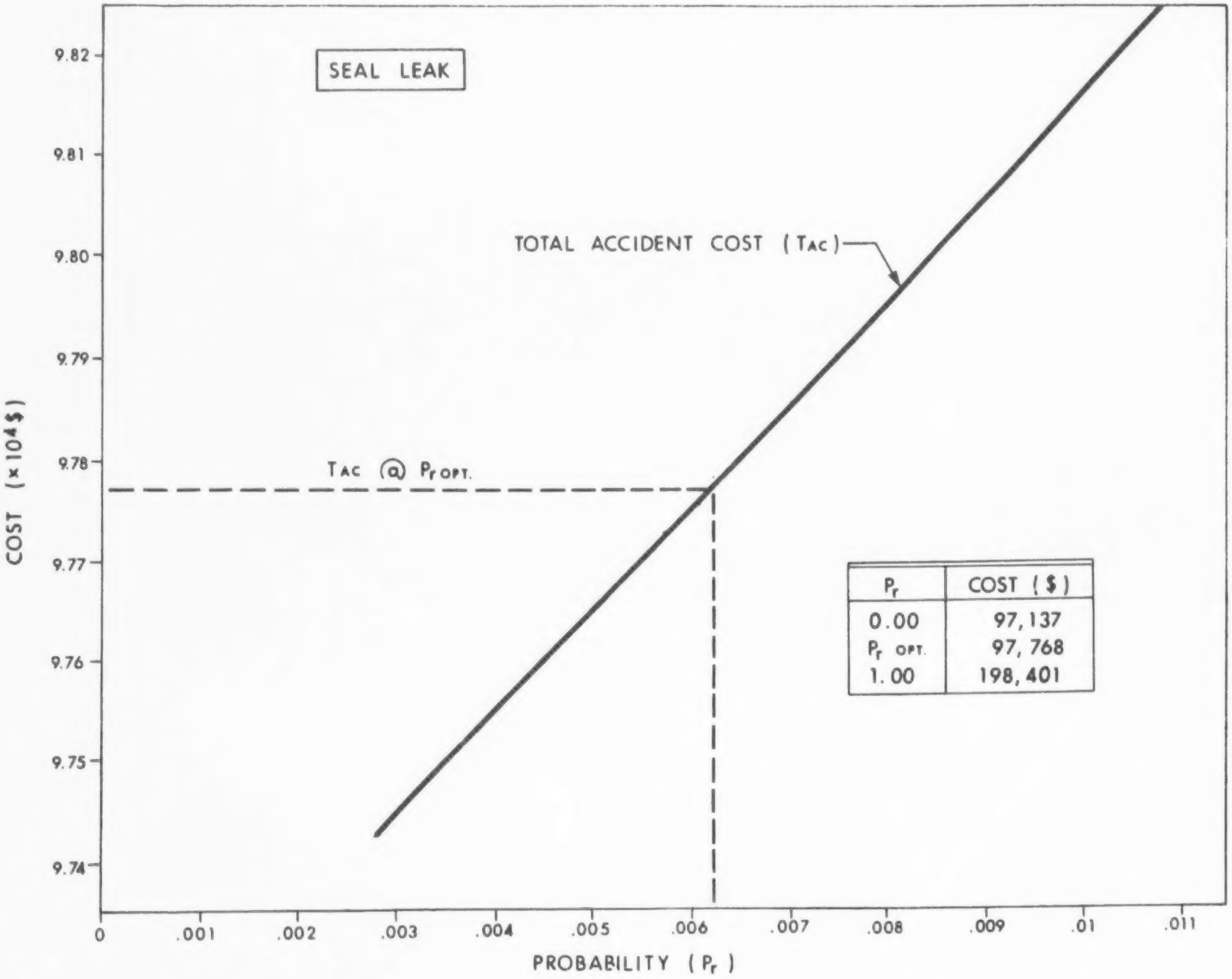


FIGURE 5.8 PLOT OF TOTAL BULK PLANT COST VS. PROBABILITY OF SEAL LEAK



P_r	COST ($)
0.00	97,137
P_r OPT.	97,768
1.00	198,401

FIGURE 5.9 PLOT OF TOTAL ACCIDENT COST VS. PROBABILITY OF SEAL LEAK

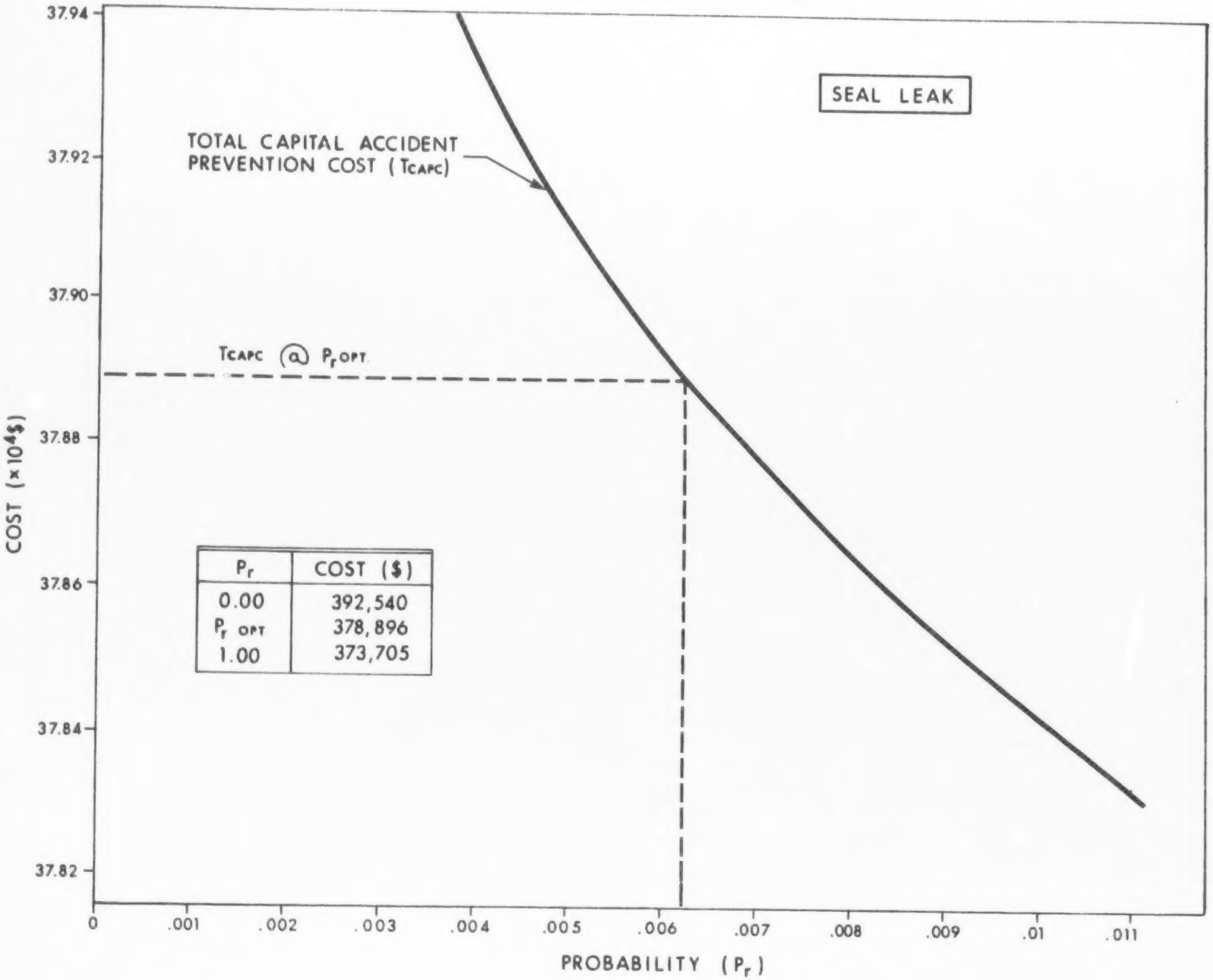
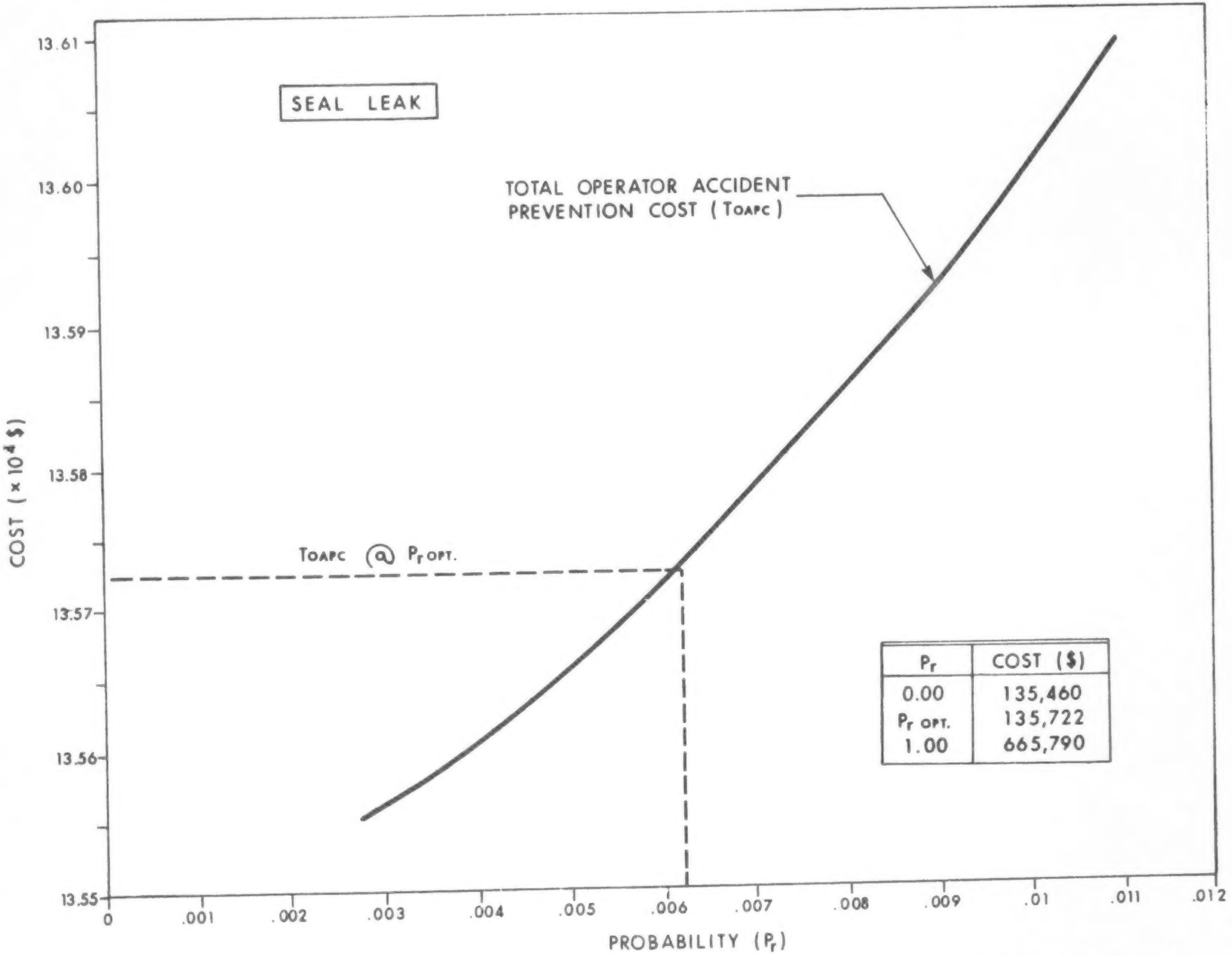


FIGURE 5.10 PLOT OF TOTAL CAPITAL ACCIDENT PREVENTION COST VS. PROBABILITY OF SEAL LEAK



P_r	COST (\$)
0.00	135,460
P_r OPT.	135,722
1.00	665,790

FIGURE 5.11 PLOT OF TOTAL OPERATING ACCIDENT PREVENTION COST VS. PROBABILITY OF SEAL LEAK

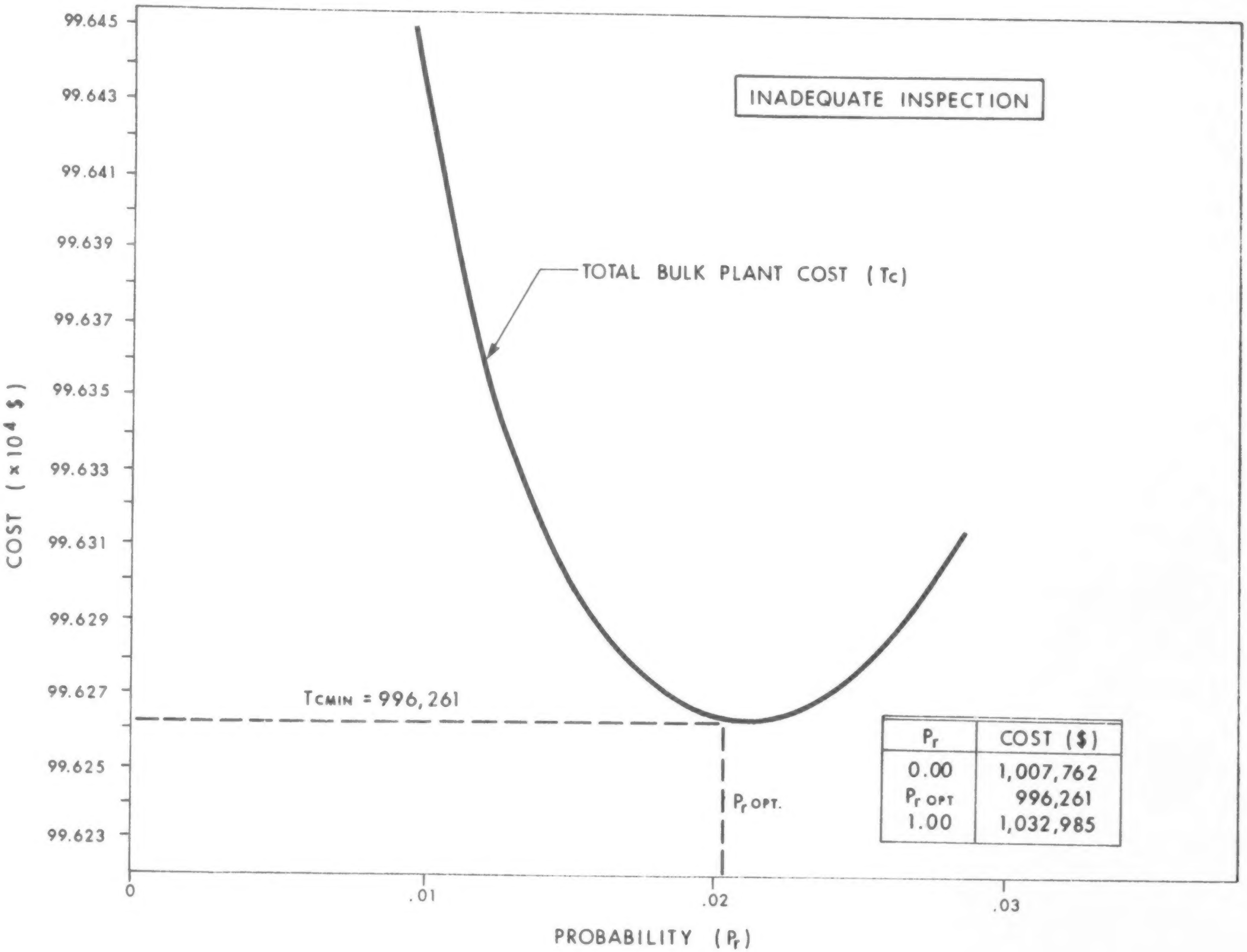
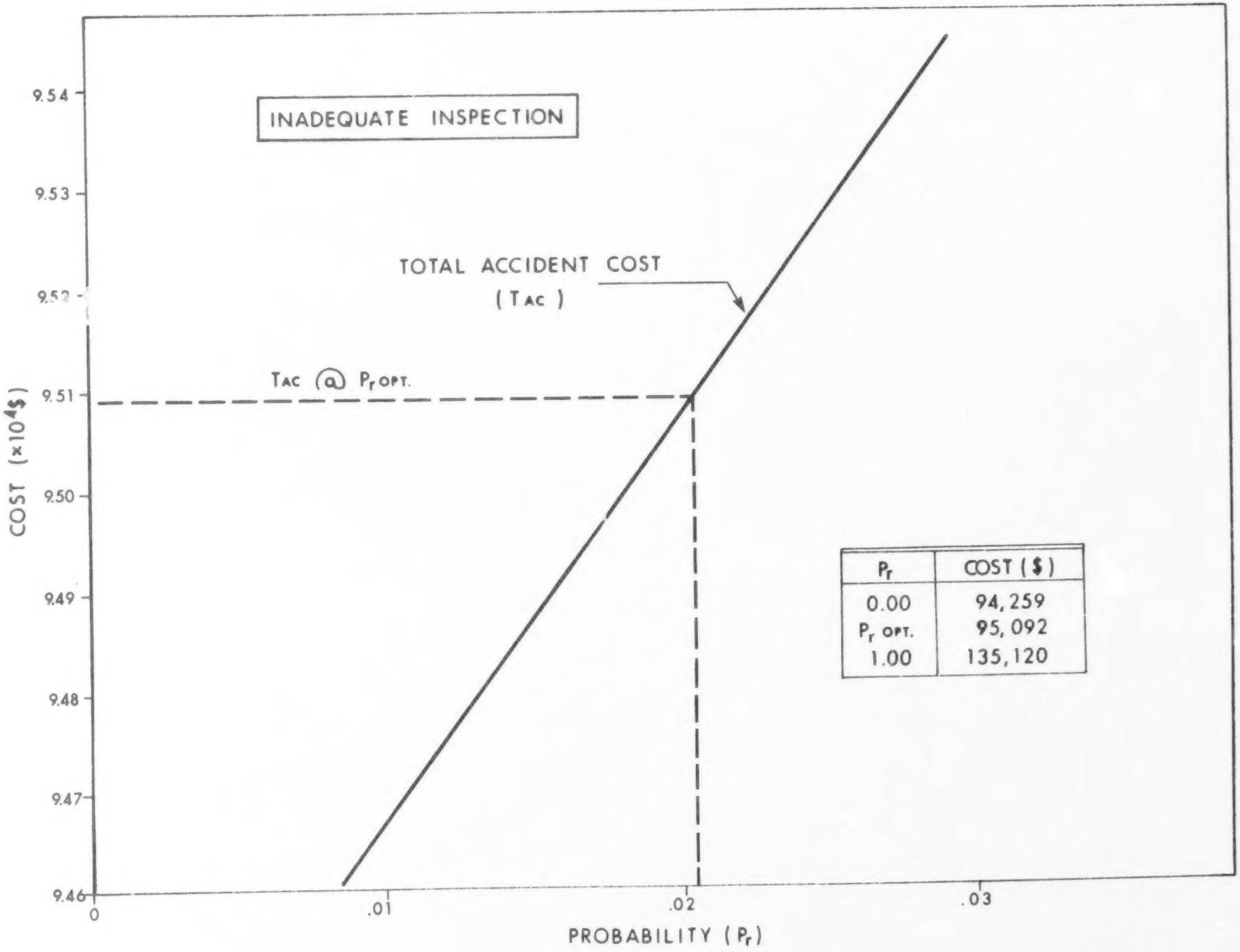
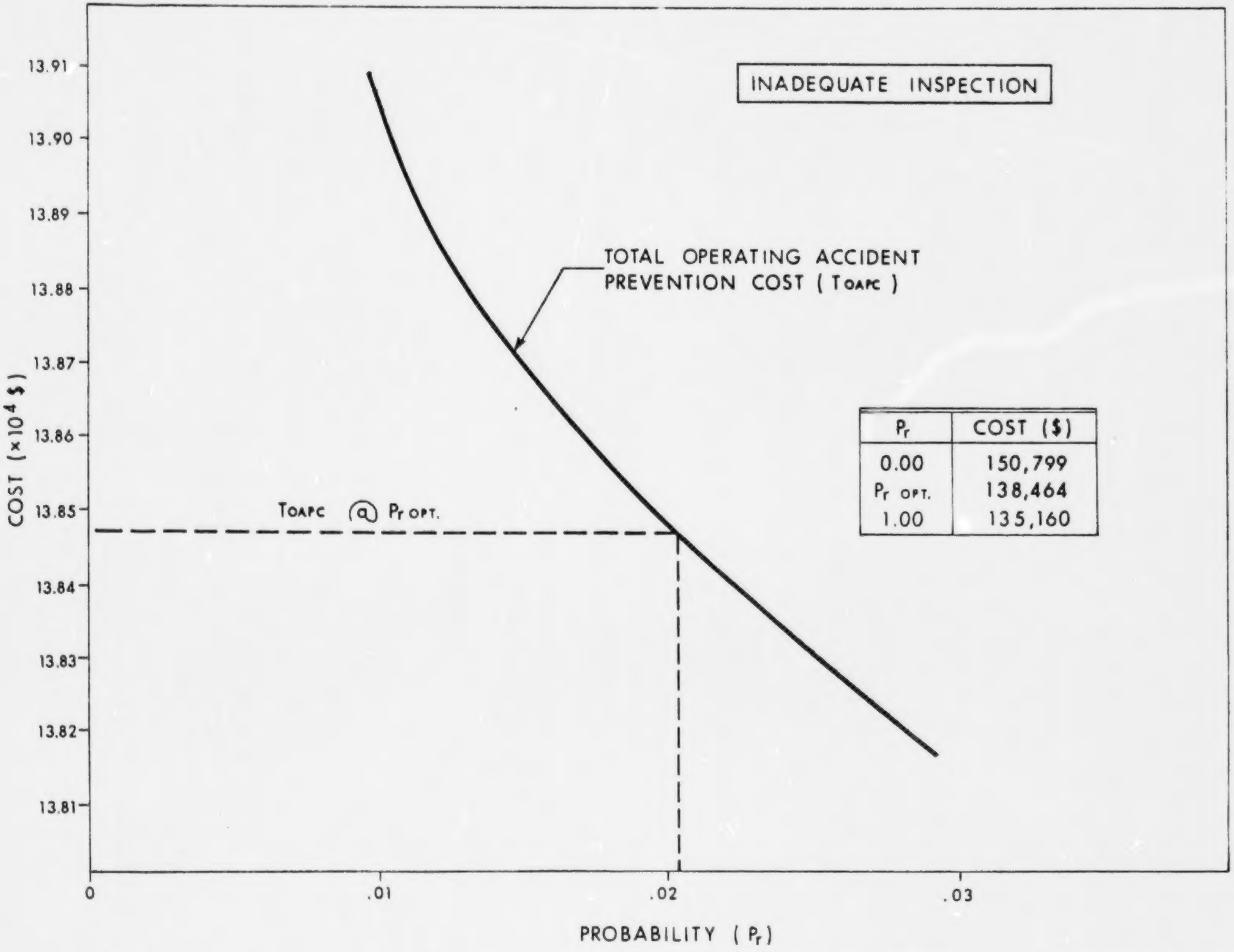


FIGURE 5.12 PLOT OF TOTAL BULK PLANT COST VS. PROBABILITY OF INADEQUATE INSPECTION



P_r	COST ($)
0.00	94,259
P_r OPT.	95,092
1.00	135,120

FIGURE 5.13 PLOT OF TOTAL ACCIDENT COST VS. PROBABILITY OF INADEQUATE INSPECTION



P_r	COST ($)
0.00	150,799
$P_{r\ opt.}$	138,464
1.00	135,160

FIGURE 5.14 PLOT OF TOTAL OPERATING ACCIDENT PREVENTION COST VS. PROBABILITY OF INADEQUATE INSPECTION

5.4.1 Optimization Scenario No. 1 - Two Events

Table 5.6 summarizes the results for the optimization of the following two events:

(a) Overestimate available capacity.

(b) Inadequate tank lining.

Details follow:

(1) Basic Events to be Optimized

(a) Overestimate available tank capacity

Accident type - Tank Overflow.

Error classification - Operator error.

Initial $P_r = 0.004 = P_{r_{base}}$.

(b) Inadequate tank lining

Accident type - Tank leak.

Error classification - Design error.

Initial $P_r = 0.002 = P_{r_{base}}$.

(2) Probability Development

(a) Overestimate available tank capacity

With $P_r = 0.004$ indicating the probability of having at least one error per tank filled, the average number of this type of error made during the course of a year is 0.004/tank x 18 tanks/operation x 20 operations/year = 1.44 errors/year.

All of these errors do not lead directly to tank overflow. For example, filling an empty vessel to half its capacity,

TABLE 5.6

BULK PLANT OPTIMIZATION - SCENARIO #1

Tree	Events Investigated	Cost Group Comparison	Costs ($)		
			Base	Optimum	Δ Cost
T O F	Overestimate Available Capacity (a)	Accident Cost	9663	9178	-485
		Op. Acc. Prev. Cost	18630	18982	352
		Cap. Acc. Prev. Cost	35946	35946	-
T L	Inadequate Tank Lining (b)	Accident Cost	21961	19082	-2879
		Op. Acc. Prev. Cost	18090	18090	-
		Cap. Acc. Prev. Cost	70479	70932	453
Overall Bulk Plant Cost Scenario Incorporating the Above Effects		Total Accident Cost	99162	95720	-3442
		Total Oper. Acc. Prevention Cost	136960	137312	352
		Total Cap. Acc. Prevention Cost	377705	378158	453
		Total Accident Prevention Cost	514660	515470	810
		Total Bulk Plant Cost	998830	996190	-2640

overestimating available capacity will not result in overflow.

An employee who takes note of the tank gauge during filling, will probably realize the error and take steps to correct it before an overflow occurs.

Consequently, it has been estimated that only about 30% of these errors lead directly to overflow. Therefore, CF = 0.3 (consequence factor) and we get 1.4 x 0.3 = 0.45. On average therefore a tank overflow will only occur once every two years as a result of an operator overestimating available tank capacity.

This kind of error usually occurs when an operator overestimates available tank capacity in calculating the filling time, then leaves the tank unattended scheduling his return for the time he predicted the operation is to be completed. Upon his return the tank will therefore already be overflowing.

(b) Inadequate tank lining

Inadequate tank lining is a design error that would normally cause a failure within the first five years of operation. Setting P_r = 0.002 would therefore mean that ≈ 2/1000 tanks will fail because of a design error in selecting the appropriate liner.

The probability is based on a tank leak occurrence in any one tank during any one operation because it seems natural to assume that the rate of use is a function of lining durability design. Therefore, 0.002 x 18 tanks/operation x 20 operations/year, therefore 0.72 tanks/year are expected to be subject to error in the selection of suitable linings. The consequence factor, CF, in this case is 0.9. That is to say that 90% of the errors of this type would lead to leak. This seems reasonable as there exists little defense in preventing leakage should such a failure occur. It follows that the number of tanks/year leaking due to wrong selection of suitable lining is 0.72 x 0.90 = 0.65. About two tanks in three years will therefore suffer leakage problems as a result of error in selecting suitable linings. It is assumed that there are no safety provisions for this type of failure.

(3) Bulk Plant Costs Results

(a) Overestimating available tank capacity.

From the optimization program it can be noted that increasing operator prevention cost by $352/year will lower total accident cost by $485/year.

Capital accident prevention costs for operator errors are just a fraction of the operator accident prevention costs, and are therefore left unchanged since those contributions normally remained fixed. For example, allocating a small area within the plant for training purposes or reserving a room for in-class instruction, results in costs that are quite insensitive to performance.

At first inspection, it may seem to the reader that a saving of 485 - 352 = $133/year, hardly seems worthwhile. It must be stressed, however, that this saving is the contribution for just a single basic event, and although it may be argued that the actual value calculated is not meaningful because of the insuperable task of allocating the time spent in a general program followed by costs associated with this time to those topics that act as direct training to prevent errors suggested, it should be accepted that the contributions of each collectively could amount to a significant saving over an entire program.

In this case, the increased operator costs amount to ≈ 372/7 ≈ $50/operator/year. These additional training costs can be realized through increased frequency of meetings, audio visual aids such as video tapes, films or slides to supplement lectures, special discussions, and in-field experience.

Another method of decreasing accident cost could involve the additional cost of time spent in selecting an operator who would be more appropriate for the job; restructuring the organization to accommodate the hiring of a more experienced operator, and replacing operators with some experience, by more junior personnel.

(b) Inadequate tank lining

Again, applying the optimization program, the latter suggests that an increase in capital accident prevention costs of \$53/year will result in a saving of \$2,879 currently meted out as accident costs.

The event under consideration is a design error, and has no corresponding operator accident prevention costs because the plant is a new installation. This can be interpreted as suggesting that a careful intensive examination by design personnel in studying different lining materials, and the effects different products stored have on them, could save approximately \$3,000 per year in repair costs. The design improvements cost would most likely not amount to \$453/year since the additional costs would be absorbed in continuing research, expected for any installation.

The analysis reveals that by optimizing the two basic events under study, namely an operator overestimating available tank capacity before filling, and design hours spent in adjudging suitable tank linings, accident costs can be decreased by \$3,442 or (3442/99162) x 100 = 3 1/2%, simply by increasing accident prevention costs by \$810 to yield a net decrease of \$2,640 in total bulk plant costs.

5.4.2 Optimization Scenario No.2 - Seven Events

Table 5.7 summarizes the optimization results for the following seven events:

(a) Gauge failure.

(b) Tank corrosion.

(c) Inadequate foundation design.

(d) Operator carelessness.

(e) Poor inspection.

(f) Inadequate fire fighting equipment.

(g) Sabotage.

(1) Basic events to be Optimized

(a) Gauge failure

Accident type - Tank overflow

Error classification - Equipment failure

$P_r = 0.0025 = P_{rb}$.

(b) Tank corrosion

Accident type - Tank corrosion

Error classification - Equipment failure

$P_r = 0.0035 = P_{rb}$.

(c) Inadequate foundation design

Accident type - Tank corrosion

Error classification - Design error

$P_r = 0.0003 = P_{r_{base}}$.

TABLE 5.7

BULK PLANT OPTIMIZATION - SCENARIO #2

Tree	Events Investigated	Cost Group Comparison	Costs ($)		
			Base	Optimum	Δ Cost
T O F	Gauge Failure (a)	Accident Cost Op. Acc. Prev. Cost Cap. Acc. Prev. Cost	9663 18630 35946	8792 16660 37518	-871 -1970 1572
T L	Tank Corrosion (b)	Accident Cost Op. Acc. Prev. Cost Cap. Acc. Prev. Cost	21961 18090 70479	18482 15927 73394	-3470 -2163 2915
T R	Inadequate Foundation Design (c)	Accident Cost Op. Acc. Prev. Cost Cap. Acc. Prev. Cost	6187 28390 89300	6441 28390 88925	254 - -375
A E S	Operator Carelessness (d)	Accident Cost Op. Acc. Prev. Cost Cap. Acc. Prev. Cost	11853 21500 30730	11406 21910 30730	-447 410 -
A E L	Poor Inspection (e)	Accident Cost Op. Acc. Prev. Cost Cap. Acc. Prev. Cost	35391 22100 35650	31394 23583 35650	-3997 1483 -
F / E	Inadequate Fire Fighting Equipment (f)	Accident Cost Op. Acc. Prev. Cost Cap. Acc. Prev. Cost	2657 21850 105650	3252 30290 91742	395 8440 -13908
O T H	Sabotage (g)	Accident Cost Op. Acc. Prev. Cost Cap. Acc. Prev. Cost	11451 6400 9950	10699 6817 9950	-752 417 -
Overall Bulk Plant Cost Scenario Incorporating the Above Effects		Total Accident Cost	99162	90468	-8694
		Total Oper. Acc. Prevention Cost	136960	143577	6617
		Total Cap. Acc. Prevention Cost	377705	367856	-9849
		Total Accident Prevention Cost	514660	511480	-3180
		Total Bulk Plant Cost	998830	986950	-11880

(d) Carelessness

Accident type - Ancillary equipment spill

Error classification - Operator error

$P_r = 0.15 = P_{r_{base}}$.

(e) Poor inspection

Accident type - Ancillary equipment leak

Error classification - Operator error

$P_r = 0.12 = P_{r_{base}}$.

(f) Inadequate fire fighting equipment

Accident type - Fire/explosion

Error classification - Equipment failure

$P_r = 0.08 = P_{r_{base}}$.

(g) Sabotage

Accident type - Other

Error Classification -

$P_r = 0.0056 = P_{r_{base}}$.

(2) Interpretation and Discussion

(a) Interpretation and Discussion

The base probability for gauge failure was 0.0025 or 25/10,000 gauges fail on tanks/operation/year, or 1 gauge failure annually. The consequence factor, CF, for gauge failure was 0.75. That is, because a gauge failure may occur during the filling of a quite empty tank to less than full capacity 0.9 x 0.75 = 0.68.

P_r = 0.00105 at the optimal level, hence the P_r has fallen to 0.378 x 0.75 = 0.28, or 1 gauge failure every four years that leads to overflow. This is achieved by increasing CAPC by $1,570, decreasing OAPC by $1,970, resulting in a decrease in accident cost of $870. This suggests that more money spent initially on quality gauges will reduce both accident costs and maintenance costs in the long run. It is assumed that this case does not include fail-safe alarms.

(b) The base probability for tank corrosion was P_{rb}=0.0035 or 35/10,000 or 1.26 tanks fail/year from corrosion. CF = 0.9, that is to say that if corrosion occurs in a tank a leak is bound to occur, simply because corrosion within a tank most frequently on its bottom, an area difficult to monitor, and an area often left unattended.

More than one tank a year will therefore leak product as a result of corrosion on average. The optimal level is P_r = 0.00119 which indicates a failure of this nature causing spill about once every 3 years. This is achieved by decreasing the related operating accident prevention expenditure by $2,200 and increasing capital accident expenditure by $2,900, resulting in an annual reduction of accident costs of $3,500. A portion of the cost went towards contingency operations preventing oil collected underground through tank seepage to migrate towards neighbouring water bodies. This implies that the purchase of better quality shell material liners will result in less frequent inspections and lower repair costs, paying off in the significant reduction of related accident cost.

(c) Inadequate foundation design

The base probability is P_{rb} = 0.0003 or 3/10,000 tanks/operation/year suffer problems related to inadequate foundation design. CF = 0.9 therefore 0.0003 x 0.9 = 0.00027 so that every 10 years a tank will suffer a foundation design problem that would result in rupture.

The P_r at the optimum level = 0.0006 x 0.9 = 0.00054 increasing the failure rate to once every 5 years. This is achieved by reducing capital expenditure by $375/year and allowing accident cost to increase by $245. The program optimizes in terms of economic reasoning which implies that since costs of clean-up are still less than cost of prevention for a 1:5 year failure rate the optimal probability is achieved by allowing for a higher probability of failure. Rational judgement in this case would weigh the ability of doubling the mean time between failures from 5 to 10 years against the insignificant amounts saved by risking a failure every five years and would certainly seek to avoid the latter. The catastrophic potential of the latter would also make any increases in the failure rate unwise. If it appeared that prevention costs greatly exceeded accident costs associated with failure, then it could be considered sound business judgement to take the risk.

In any case, the tanks require foundations that are of sufficient strength to support the tanks for some time, necessitating implicitly a liberal amount of capital for accident prevention. The conservative design criteria used generate only a small probability of failure due to inadequate design. The costs of the accidents in the long run are therefore smaller than the cost benefit of a minimum relaxation of original design specifications.

(d) Operator Carelessness

Errors in operating procedures constitute the primary cause of spill incidents. Among these negligence through carelessness can be considered to be one of the most commonly occurring error of this type.

The base P_{rb} = 0.15, or 0.15 x 20 operations/year or 3 errors/year related to ancillary equipment spill.

It should be noted that only errors with a reasonable probability of occurrence are considered. These are errors that command a reasonable potential for spill.

The consequence factor, CF, is about 0.3, or $3 \times 0.3 \approx 1$ spill/year. The P_r at the optimal level is 0.12, lowering the spill rate to 0.75/year.

The small change implies that carelessness, even at the optimal level results in a significant level of accident. This can be explained by the nature of the error which is inherent to varying degrees in all men. Even experienced operators have been known to make costly errors under familiar circumstances for any of the myriad of reasons that stem from the complexity and inquietude of the human psyche. Marital, financial, and health problems are major contributors to situations that could cause a normally efficient well-trained individual to affect an error.

For this plant the P_r is reduced from 0.15 to 0.12 by increasing operating accident prevention costs by $410, resulting in a decrease in accident cost of $447. It seems from these figures that accident cost is not that sensitive to operating accident prevention cost in that onoy a small net saving is realized. This can be expected from the difficulties incurred in lowering this type of error through training, or by imposing penalties.

A greater benefit might be derived from funds directed towards promoting better interpersonnel communication and crisis relief.

(e) Poor Inspection

Poor inspection is an operator error that is deemed responsible for a signficant part of ancillary equipment leaks. P_{rb} = 0.12 therefore 0.12 x 20 ≃ 2 1/2 sig. errors/year. CF = 0.4 therefore 0.4 x 2.5 = 1 sig. leak/year. On the average one incident of ancillary equipment leak occurs annually. At the optimum level P_r = 0.0021 which limits incidents of this nature to 1 every 5 1/2 years.

This is achieved by increasing the annual operating costs by $1,500 and decreasing the annual accident cost by $4,000. The $1,500 would be spent either on more intensive training programs or on additional wages paid a more experienced employee, or a combination of both.

The poor inspection accident event refers principally to those leaks that stem from problems that can be normally detected through routing inspection. The ratio of cost prevention to benefits derived would be normally much higher for leaks not easily detected through inspection.

(f) Inadequate Fire Fighting Equipment

The base probability for inadequate fire fighting equipment is P_{rb} = 0.08. The treatment of fire prevention error events differs from other events in that fire fighting equipment is not utilized on a continuous or regular basis, like tanks or lines, but only when needed.

For this reason, the probability is not time contrained but instead reflects a general level of operability. It indicates that 8% of fire fighting equipment on site would be inadequate for intended use in the event of fire. CF= 0.9 therefore 0.08 x 0.9 = 0.07.

About 7% of the equipment would actually contribute towards failure to control and extinguish a blaze should one occur. At the optimal level, P_r = 0.144 x 0.9 = 0.13 ≈ 13% of the equipment would contribute towards the failure of fire control. From the program it was determined that allowing the P_r to slide from 8 to 13% would result in an average annual increase in fire/explosion accident cost of $600, and by spending an additional $8,500/year in operator accident prevention cost, then $14,000 could be deducted annually from the capital expenditure, resulting in a net gain of 5,000/year.

It implies that expensive capital expenditure could be substituted by less expensive operating related costs. Although this increases the probabilities of failure in fire control, the net outcome would be in the favor of the plant. Fire is an event with a very small probability and as a result the annual accident costs are very low compared to the high costs of capital. It therefore seems reasonable to expect that a good deal of that cost can be cut back without causing significant increases in accident cost.

Considerations other than economic considerations are affected by fire/explosion accidents. Where losses of lives lie in the balance of certain decisions then these consideration must be carefully evaluated.

This does not, however, imply that economic considerations must be abandoned. It is often difficult, if not impossible to assess expected accident costs associated with fires/explosions because of the numerous factors that could influence them. For example, type of tank, proximity of tanks to each other, values of neighbouring buildings, etc., size of fire, type.

The results from the program indicate that if higher operating costs ($8,500/year) were spent in the elimination of hazardous situations, training costs to familiarize personnel with situations that could lead to fire/explosion catastrophe, and contingency instruction to demonstrate how failures can be handled to avert a more serious situation, then the higher expenditures for added safety could be successfully reduce ($15,000/year).

(g) Sabotage

The P_{rb} of this event is 0.0056 therefore 0.0056 x 20 = 0.112. On the average once every ten years a facility suffers an attempted sabotage. This number naturally varies from facility to facility depending on the political or social climate involved, and could also vary from period to period within the same facility. CF = 0.9 therefore 1.12 x .9 = 1 or one spill occurs on average very 10 years as a result of sabotage.

At the optimum level, P_r = 0.002. This indicates a spill incidence rate of 1:25 years from sabotage. This is achieved at by investing an additional $25/year in operating costs reducing the annual accident costs by $750. The size of facilities makes the employment of guards to patrol the area efficiently infeasible. Allowing two or three guard dogs to patrol the area might however reduce sabotage occurrences at the expense of a small additional operating accident prevention cost.

Employing guard dogs should reduce the number of guards needed; hence, the associated small increase in cost.

(h) Summary

In summary, the net result of optimizing all these events would yield a $8,500 decrease in accident costs on an annual basis by increasing total operating accident prevention cost by $6,500/year. Capital accident prevention costs would decrease by $10,000/year. The final result would be a total bulk plant cost that would be about $12,000/year less expensive than the present operation.

5.5 Different Bulk Plant Types

A range of bulk plant types with different capacities was studied utilizing the basic program appropriately adjusted to account for various effects. Figures 5.15 and 5.16 show, respectively, the variation in total bulk plant costs with total bulk plant throughputs.

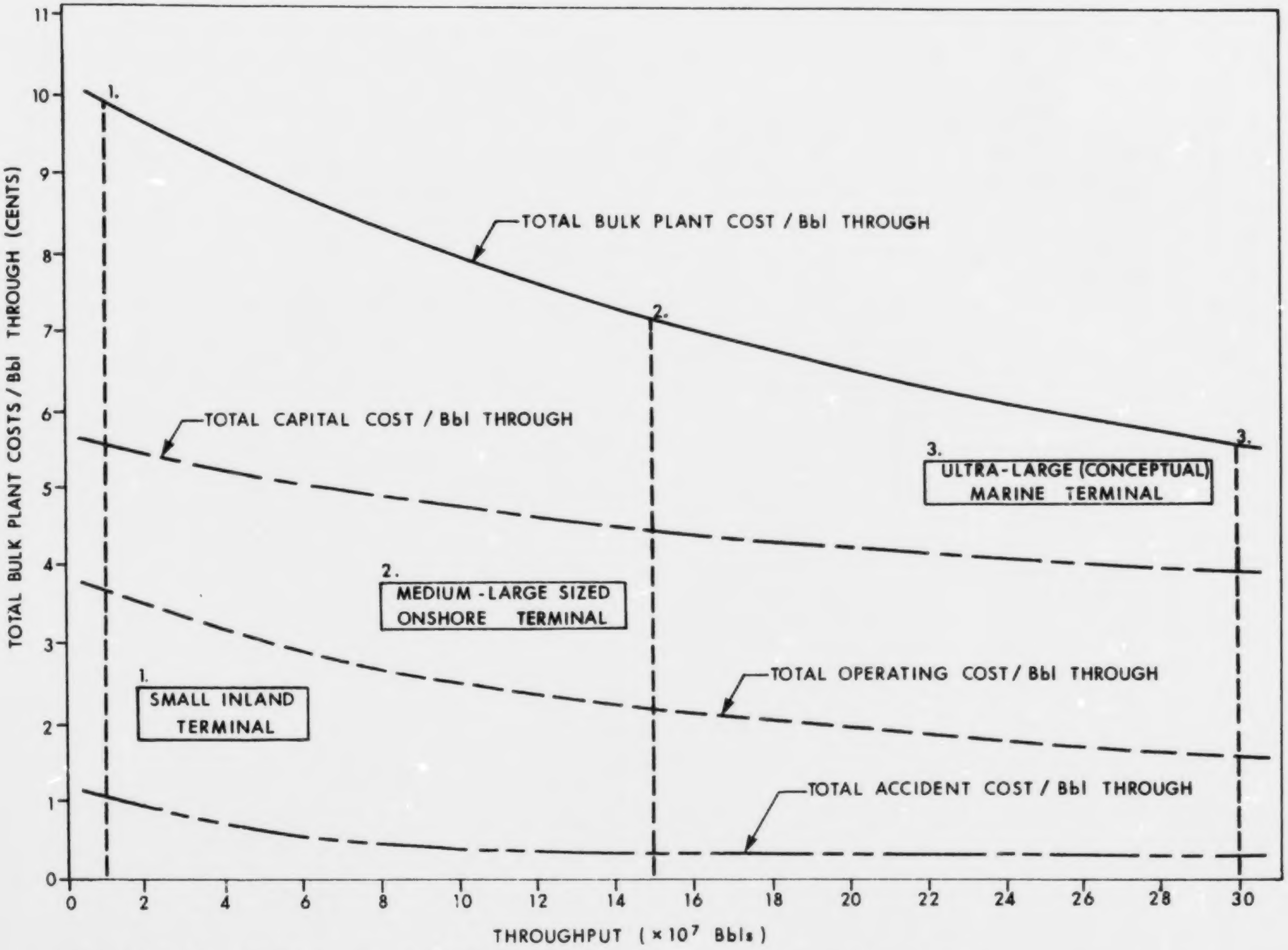


FIGURE 5.15 PLOT OF TOTAL BULK PLANT COSTS IN CENTS PER BARREL THROUGH VS. THROUGHPUT IN BBLS

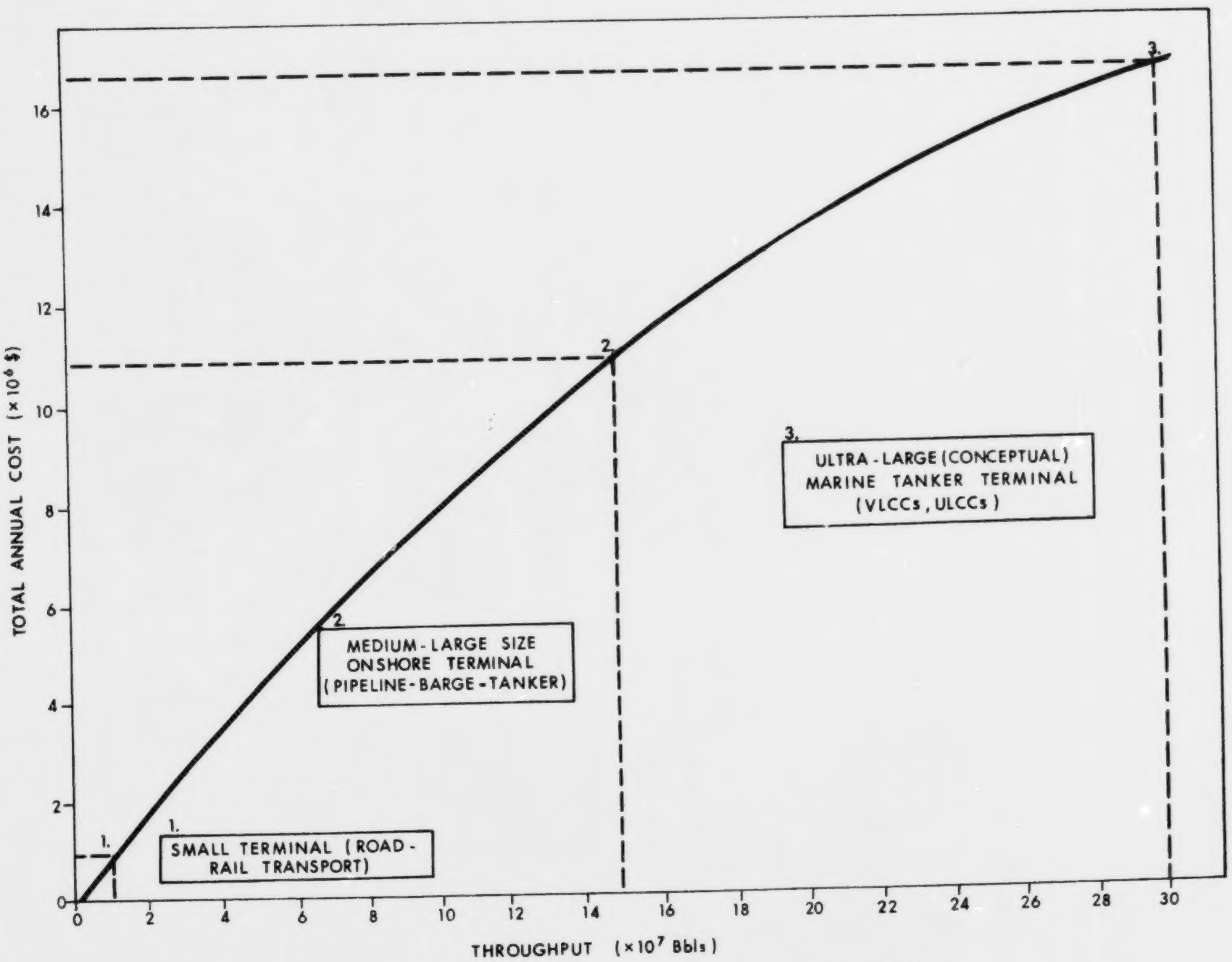


FIGURE 5.16 PLOT OF TOTAL ANNUAL COST/YEAR VS. THROUGHPUT

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 General Conclusions

This report quantifies and relates bulk plant capital, operating, and accident costs. These costs are used to optimize risk within a set of physical, operational, and economic constraints. The following main tasks were carried out:

(a) Information Gathering.

(b) Risk and Optimization Analysis.

(c) Result Generation.

In the information gathering phase, information was obtained from public and private sources on general bulk plant operations, bulk plant accident scenarios and associated statistics, bulk plant operating and capital costs, and accident costs. Operational and accident event data were relatively easy to obtain. These were available from records on a local, national and international level. Cost data relating to accident optimization was, however, particularly difficult to obtain. The definition of the boundaries between normal operation and accident prevention activities was realtively arbitrary and had to be assigned in a subjective manner. A rigorous universal definition of the distinction between accident and operating cost has yet to be generated. A heuristic definition of this distinction was made for the purposes of carrying out the current study. The body of information obtained from empirical and statistical sources served as a reasonable basis for the current work and should provide a good foundation for the execution of more rigorous analyses in the future.

A risk optimization analysis of bulk plant operations within the constraints of economics of risk was developed. The risk analysis portion of the work was carried out utilizing conventional fault tree techniques. The concept of a cost tree is relatively new in the literature. Algebraic conventions were altered in order to correspond to cost rather than probabilistic computations. Interface between the probabilistic fault treee and the associated economic cost tree through the utilization of cost factors, although relatively simple, has not previously been reported in the literature. The optimization of risk within economic constraint constraints utilizing cost and fault tree networks appears to be new. Optimization was achieved through a systematic perturbation of accident probabilities with a deterministic functional variation of associated costs. The generation of local and global maxima and minima for total plant operating and capital costs was shown to be achievable utilizing the optimization procedure. Although the validity for certain of the optimization procedures was intuitively evident, the general validity of the specific numerical economic results generated is contingent on the accuracy of some of the cost factors generated and consequently may be questionable. The general principal of risk optimization utilized herein, however, appears to have been adequately implemented through the optimization technique developed.

The results generated included specific numerical results as well as ones illustrating general trends relative to operational and economic governing parameters. The numerical results are generated utilizing a software package developed specifically for the current project. This software package may be operated in several modes, including a preliminary result generation mode and a refined analytical mode. The preliminary result generation mode only requires a small number of inputs in order to operate making it virtually universally usable. The more refined mode requires that certain internal parameters described in the report must be modified in order to reflect secondary and higher order effects in the optimization procedure. Specific numerical results generated include the following:

(a) Individual event optimization.

(b) Dual event optimization.

(c) Multiple event optimization.

(d) Plant type variation investigations.

The numerical studies reveal certain specific trends as well as more general ones outlined below.

It can generally be concluded that the costs associated with clean-up operations are an important parameter in justifying additional levels of accident prevention. That is, the higher the costs of clean-up the more incentive for the facility to minimize the incidence of spill. The costs associated with oil spill liabilities include those associated with clean-up, penalty, and remuneration to third parties. The costs of clean-up are a function of the circumstances surrounding the associated spill incident. They depend on type of product stored, environment affected, and volume spilled. Penalty and their party remuneration costs are under legislative control and can be increased to high enough levels to force facilities which demonstrate a propensity for spill related incidents to improve their measures of prevention.

The following general trends are indicated by the results of the investigation:

(a) Human error is the principal cause for spill in bulk plant operations. It is the most difficult to predict and control because of its sensitivity to operating and environmental parameters.

(b) External hazards such as sabotage, collision, weather, tsunami, and earthquakes, are uncontrollable but are normally quite insignificant.

(c) The catastrophic spill event is of principal concern because of its major contribution to spill volume.

(d) Legislation and levying of penalties adds to spill prevention motivation.

(e) As the magnitude of the spill increases, the lower the per barrel cost of accident due to the fixed set-up costs involved.

6.1.2 Specific Conclusions

(a) Operator Error

Of the seven major accident types examined, operator error during tank charging operations was the main contributing factor. Human error classification for the remaining accident types is principally related to maintenance activities to be discussed later.

From the analysis it was concluded that:

(i) Lack of experience is a main contributing factor in accidents. Inexperience may be compensated for by training programs.

(ii) Human errors are pervasive. Both training and experience fail to completely eradicate accidents due to human failings.

(iii) Operator reliability is significantly affected by the working conditions.

(iv) The implementation of the high level alarm is most beneficial if applied only in a passive capacity; that is, utilized for back-up only in an emergency situation.

(v) Operator spill incidents are significantly influenced by company policy. Management behavior influences the extent of employee participation in accident prevention.

(b) Equipment Reliability and Maintenance Errors

The relationship between equipment reliability and maintenance as an operating accident prevention activity was readily discerned from the analysis. It was established that the maintenance function could be separated into three distinct roles, namely repair, service, and inspection, each essential to the operation of any installation.

If the total annual bulk plant expenditure was minimized using the simulation model, then this implied that the following conclusions were reached:

(i) Spill incidence probability is reduced by improved training. The improvement in spill risk is, however, limited by a basic level of human unreliability that cannot be eradicated by training or experience. This is also a limiting factor on the improvement in reliability by hardware improvments.

(ii) The implementation of intricate or novel equipment may reduce accident costs, lessen maintenance costs by limiting the frequency of service or repair, and reduce subsequent downtimes that affect profitability. Analysis has, however, shown that these savings could be offset by the additional capital costs of the system, and costs incurred in providing specialized service personnel. Replacement parts when required would furthermore be more expensive.

(iii) The implementation of automatic safeguarding devices can significantly reduce spills and reduce overall operating expenditures. The utilization of high level alarms can reduce the probability of accident and reduce total bulk plan costs efficiently since such devices are relatively inexpensive. The use of a system consisting of both high level alarms and automatic shutdown apparatus would virtually eliminate any possible chance of overflow, but overall bulk plant costs would increase significantly because the latter are mot costly devices that balance out the savings due to reduced spill incidence.

(iv) Human related design and construction unreliabilities must be considered in the appraisal of the reliability of any hardware components.

(v) An inexperienced maintenance man is inclined to make more technical errors; however, an experienced individual is prone to overconfidence which can also result in spill incidents.

(vi) Surveillance of contract workers while on site is necessary.

(vii) The value of any system is limited by its cheapest components, and replacing any component with a cheaper unit can actually increase overall cost by the loss incurred on the rate of return form the original capital.

(viii) Equipment reliability is commensurate with the frequency of repair, which results in downtimes that contribute to loss profitability.

(ix) Scheduling of preventive maintenance work is more difficult than clean-up and repair costs associated with failure.

(x) Replacing worn parts rather than repairing them increases equipment reliability and reduces associated long-term costs. It should be noted that a portion of capital costs is set aside for the acquisition of the necessary spare parts.

It should be mentioned that in any reliability analysis the mid-life characteristics of mechanical equipment should provide the basis for cost-benefit analysis. Failure rates are normally higher during start-up and wearout periods and they would therefore not be representative of the unit under normal operating conditions.

(c) Design Error

Failures due to engineering design errors are those that historically have the lowest incidence of occurrence. The preparation and continuous refinements of codes and standards over the years have resulted in guidelines recognized and used throughout the design industry. Hazard analysis a an important aspect of the designer's function, enabling him to identify weaknesses in the system.

Factors of safety must be accurately resolved in the design stage. This requires the designer's understanding of the total operation, and ability to determine cost-benefit relationships.

Designers must also carefully monitor on-stream operations to identify problem areas that require further resolution. These problems may relate directly to operational safety or design shortcomings.

It has been concluded from the analysis that in the majority of case examined, allocating more funds to the design phase of the operation will significantly lower annual total costs by decreasing operating risks and hazards that often result in high accident costs. The importance of plant layout is, for example, paramount in any operation not only in the considerations or safety, but also to ensure the smooth, efficient transfer of petroleum products reflecting directly upon profitibity.

The importance of rigorous studies of hazard analysis is emphasized.

Fire protection is a prime example illustrating the importance of design considerations in the petroleum handling operation. Even though the frequency of fire occurrence in this industry is smaller than most other accident types, the disastrous ramifications of a fire/explosion incident justify the extensive capital and operating accident prevention expenditures spent on deluge facilities, foam generating systems, novel instrumentation, improved communications networks, personnel safety apparatus, fire vehicles, foam injection, water delivery and extinguishing systems, or fire brigade training. Tank layout, proximity to water sources, piping, alarm and hydrant schematics, proximity to neighbouring fire stations, diking, etc. are all important design considerations that must be exhaustively studied to ensure that desired levels of fire safety are satisfied. Diking, mentioned above, as an example of a design consideration, does not derive its utility principally through the containment of petroleum that results from overflows or leaks in a normal environment, but rather by preventing burning product resulting from a tank explosion from igniting neighbouring tanks. Where a plant is located near a sensitive environment, diking would also be an effective cost-benefit investment for general spill containment.

(d) Scale Effects

In the analysis of facilities with different throughputs, numbers of annual operations and numbers of tanks filled per operation, the following conclusions are reached:

(i) The transfer of petroleum is the primary contributor to spill incidence, and the greater the number of transfers, the higher the incidence of loss.

(ii) The greater the annual throughput, the lower the per barrel total costs.

(iii) Total annual costs increase at a decreasing rate as the size of the plant, measured by the annual throughput, increases.

(iv) As the size of the terminal increases, oil spill losses tend to decrease suggesting that, in addition to better contingency equipment, larger forces of personnel justify the operation of an organized extensive training program that is directed at both minimizing the occurrence of spill events and the development of a contingency plan once a spill has occurred to minimize its effects.

6.2 Recommendations

6.2.1 Operational Recommendations

Recommendations directed at optimizing bulk plant operations are as follows:

(a) Formal training programs must be extended beyond the initiation period of an employee's association with the company. Periodic refresher courses reviewing operating procedures and introducing new industrial innovations preserve the employee's prime level of efficiency.

(b) A high level tank alarm installed on each tank will reduce operating costs by reducing costs incurred though overflow incidents. A redundant system consisting of both high level alarms and automatic shutdown devices would not be economically viable, and is therefore not recommended.

(c) Implementation of specialized equipment can be justified if savings in accident cost and productivity exceed the cost of the hardware and the increase in costs associated with specialized maintenance.

(d) Errors in plant design are normally the least significant with respect to their contributions to incidents of failure leading to the spill of petroleum. Small improvements in the design stage could, however, alleviate costly human errors during operation.

(e) Hiring experienced personnel to perform certain tasks that could be as effectively done by less experienced personnel raises operating costs above the optimum level.

6.2.2 Study Recommendations

Recommendations for further investigative, analytical, and data collection work related to the improvement of risk optimization studies of the type carried out and described herein are as follows:

(a) The development of comprehensive national system of spill documentation identifying volumes spilled, material spilled, source, cause, extent of damage, percent recovered, contingency procedures effected, and itemizing all costs associated with clean-up including third party and penalty costs.

(b) The improvement of optimization techniques in the manipulation of similar problems seeking optimal solutions.

(c) The refinement of fault tree methodology to better handle industrial problems that require an understanding of the relationship between the probabilities of failure, and the associated costs of prevention, directed towards maximizing economic efficiency.

(d) The comprehensive, in-depth investigations of a number of existing operations to establish an effective data base applicable to the problem under study. Published information is less operative because of interpretations and inferences made.

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